THE EFFECT OF QUEUE SELECTION METHODOLOGIES ON THE VARIABILITY OF DISCRETE NETWORK FLOW

A THESIS

Presented to

The Faculty of the Division of Graduate

Studies and Research

By

Richard L. Beller

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Operations Research

in the School of Industrial and Systems Engineering

Georgia Institute of Technology

June, 1974

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SUMMARY

This research concerns the investigation of the differences in discrete network flow patterns under various dispatching methodologies. The study has used a job-shop type simulation model in which the flow actually consists of jobs or units of work. The shop is dynamic in nature in that work is continually entering and leaving the shop. Three different loading approaches were used with the simulation model: uncontrolled arrivals, a job pool with a mathematical algorithm, and a job pool with a heuristic loading algorithm. Nine measures of network flow were formulated and comparatively analyzed with traditional job-shop performance criteria and shop balance criteria with each loading approach to determine similarity of information content. Six dispatching rules were used to control the shop and produce the values of the performance criteria. By isolating any one performance measure, the capability of the dispatching rule to effect network flow was ascertained and the rules were ranked in order of effectiveness.

Additionally, the arrival process to a machine selected at random was studied to determine the applicability of the Jackson decomposition principle to this model and to test its applicability to dispatching rules other than first come-first served. The simulation model was also run at a

10% higher utilization to determine whether the capability of the performance criteria to measure effectiveness had deteriorated.

It has been shown that the network flow measures contain equivalent information content as the traditional and shop balance criteria. Also, it was observed that the ranking of the dispatching rule in order of efficiency was not markedly influenced by the loading approach. The Jackson decomposition principle has shown that this simulation model can be analyzed as independent machine centers for the following dispatching rules: dynamic slack, dynamic slack per operation, expected work in next queue, shortest processing time, and first come-first served. The job pool concept has been shown to reduce the variance of the arrival process by a decrease in the distribution parameter. When the shop was run at 10% higher utilization, the performance criteria generally retained its capability to measure effectiveness.

CHAPTER I

INTRODUCTION

The purpose of this research is to investigate the differences in discrete network flow patterns under various dispatching methodologies and to identify relevant measures of network flow. The study has used a job-shop type queueing network in which the flow actually consists of jobs or units of work. The theme of the research has been the effect of dispatching rules upon the pattern of flow within the job shop. This instigated the formulation of nine measures of network flow, described in Chapter III, which are analyzed comparatively with traditional job-shop measures and with more recently developed job shop balance measures. This research has used six dispatching rules to control the shop and to produce the resultant values of the performance criteria for analysis. By isolating any one performance measure, the capability of the dispatching rule to perturb network flow could be ascertained and the rules ranked in order of effectiveness.

There has been considerable job-shop scheduling/ sequencing research done in the past and since the general problem has not been solved, research is continuing. As Conway [15] contends,

> The general job shop problem is a fascinating challenge. Although it is easy to state, and to visualize what is required, it is extremely difficult to make any progress whatever toward a solution. Many professional people have considered the problem, and all have come away essentially empty-handed. Since this frustration is not reported in the literature, the problem continues to attract investigators who just cannot believe that a problem so simply structured can be so difficult until they have tried it.

The job shop problem is simply stated. There are M machines which can process N jobs, which are continuously entering and leaving the shop. Each job has a determined order in which it is processed through the machines. It is assumed that each machine cannot work on more than one job at a time and that processing required by a machine cannot be done on any other machine. The problem is to find the best production plan in sequencing the N different jobs on each machine so as to optimize some measure of performance or criterion. Such a plan is called an optimal one.

In addition to the challenge of solving the problem, there are a number of other reasons for the research. The primary reason is the cost of idle machinery and idle workers, or alternately, the much higher cost of overtime and customer dissatisfaction from lateness of job completion. In some situations, scheduling too much work for the shop would create the need to lease extra machinery to deviate from the expected use of a machine. Late jobs will cause lost time for management people who must console customers while attempting to push through an order upsetting previously organized production runs. This research may provide insight into the problem by giving management more knowledge about controlling the job shop rather than accepting results without recourse. Many other economic and realistic reasons for this research can be stated, but even with this overview the importance of a solution to this problem is certainly clear.

A simulation approach was utilized in this research for two primary reasons, First, the analytical equilibrium solution to a queueing system is dependent upon the input parameters once more than two machine centers are in the network, i.e., a general equilibrium solution exists for systems in which the numbers of servers is strictly less than three and the number of waiting positions or queue length is fixed (Weber [65]). In fact, the analytical solution requires such increasingly complex expressions for specific systems (more than two servers), that the calculations alone suggest that economical application of the results would be limited to rather simple systems. The second reason is that systems of realistic size can be simulated under various conditions. For example, a simulation model can use any probability distribution, even empirical distributions, whereas the analytical solution is typically limited to poisson arrivals and exponential repair times and service times. To state the second reason in another way that is certainly more emphatic, Conway [15] asserts that for interrelated networks of realistic size there are no applicable theoretical queueing results.

Nanot [43] places simulators into two groups: (1) Models that use sequencing procedures from actual shops and then determine the procedure to optimize a measure of performance under specific conditions. The problem is to find the proper value for the parameters that optimize the criterion. In this case, the simulator is simply a method for evaluating a complicated function; and (2) models which include many factors that have a bearing on the operation of the shop and with which controlled experiments isolate the effects of some particular variable upon the criterion.

To quote Jackson [31],

> The reason for realizing a mathematical model by means of a simulator is to study its properties experimentally. The simulator provides a basis for applying the broad approaches of laboratory science to certain complex mathematical models, in order to discover useful generalizations about them; that is, for engaging in 'experimental mathematics'.

Three basic approaches have been attempted in solving the job-shop problem: analytical flow models, analytical job-shop (or queueing models) and simulation models. These three models will be discussed later with their relevance to the literature. The general approach to this research is, as previously mentioned, of the simulation model class. The specific performance measurements, which have been oriented to measurements of the job shop rather than individual jobs, will be studied with various dispatching rules.

Deane [16] used a simulation model to study a job shop with an uncontrolled, i.e. random, arrival process. Using workload balance measures as his optimization criteria, he was able to improve these measures whenever he applied his new flow controlled scheduling methodology. Irastorza [26] used a simulation model to study a job shop that controlled the arrival processing by placing arriving jobs in a pool and then releasing them to the shop with a loading algorithm. His performance criteria were workload balance measures and traditional measures, and in conjunction with the job pool and loading algorithm, he also was able to show improvement. Thus, Deane and Irastorza both elicited improvement in the performance measures of the job shop, but with antithetical procedures. Hence, the hypothesis of this research is that each experimenter had, in some way, effected the system parameters of the queueing network. This research effort has been to investigate this hypothesis. By defining performance measures that evaluate attributes of the queueing network, both the controlled and uncontrolled arrival process have been studied. An analysis was performed to determine the difference across the six dispatching rules and the order of performance. Additionally, the determination of the information content of utilizing network flow measures was ascertained by a comparative analysis with the traditional measures and the workload balance measures. This knowledge will give insight into the general job shop problem and to the reason that both researchers were able to provide increased shop effectiveness with their contributions to the field.

This research is presented in the following chapters. Chapter II provides an overview of a job shop with definitions and gives a review of the relevant literature. Chapter III discusses performance measurement and describes the measures collected in this research. Chapter IV explains the simulation model used in this research, the validation process and the design of the experiment. Chapter V presents the results of the experiment and the comparative analysis performed. Chapter VI gives the conclusions of the research and recommendations for extensions of this work.

CHAPTER II

OVERVIEW OF JOB SHOP AND REVIEW OF THE RELEVANT LITERATURE

2.1 Job Shop Overview

2.1.1 Job Shop Definitions

A job shop in this research has been considered a machine/production shop, although it could have just as easily been defined as the scheduling of hospital patients (jobs) on a limited number of test equipment (machines), or the scheduling of jobs through various operations of a computer installation. The usage of terms in this paper need to be given for clarity since there is little standardization in the terminology of scheduling. In fact, some people disagree that sequencing and scheduling can be the same thing, although in this research they are considered equivalent. When one is willing to assume that the processing times are known and that there is no allowed idle time, then a sequence designates a schedule. Herein the jobs are engineered before they enter the shop so the processing times are known and no idle time is permitted. Therefore the terms are synonomous.

Other terms which may need clarification are given below:

(1) Operation--the basic unit of work or most elementary task.

(2) Job--the product of this shop, the entity which is processed through the shop. A job consists of one or more operations.

(3) Machine--the work center where the operations are performed. A work center can have fixed or variable capacities.

(4) Pure job shop--a shop in which all orderings of operations through the shop are equally likely.

(5) Flow shop--a shop in which one or more orderings through the shop have higher probability of selection.

(6) Stochastic job shop--this definition is taken from Elmaghraby [17]. The probabilistic elements enter into the system in one of three forms: (1) the set of n jobs is dynamically varying in a stochastic fashion; (2) the requirements of each job (concerning route, processing times, due dates, etc.) vary stochastically; (3) the characteristics of the processors (availability, suitability, number of processors, etc.) change stochastically. The first two requirements apply to this research.

(7) Deterministic job shop--a shop in which the requirements in (6) above do not hold.

(8) Job pool--a holding area, either implicit or explicit, for jobs to remain until conditions in the shop dictate their being released for processing. The jobs arrive

at the pool in random fashion.

(9) Dispatching rule--the decision rule or queue discipline used to select the next job out of queue for processing. The discipline by which the sequence is generated.

(10) Release--a job released to the shop has completed its engineering and has been given to the shop for processing at the first machine of the job's ordering. The release of jobs to the shop is a random process.

(11) Loading--the release of one or more jobs at a time from the pool to the shop for processing at the first machine of the job's required operations.

(12) Shop balance--a shop oriented performance criteria that endeavors to spread the workload evenly over all machines or over time.

The job shop in this research could have been addressed in terms of classical network theory. Figure 1 illustrates the network of a three machine job shop which has a super source and a super sink. The work flow along the arcs would be in terms of work rate per scheduling period. The arcs would be capacitated with zero as the lower bound, and the maximum machine capacity per scheduling period, as the upper bound. However, classical network theory was not used. Instead, traditional terminology and methodology of scheduling as applied to simulation was employed.

The shop in this research is dynamic since jobs

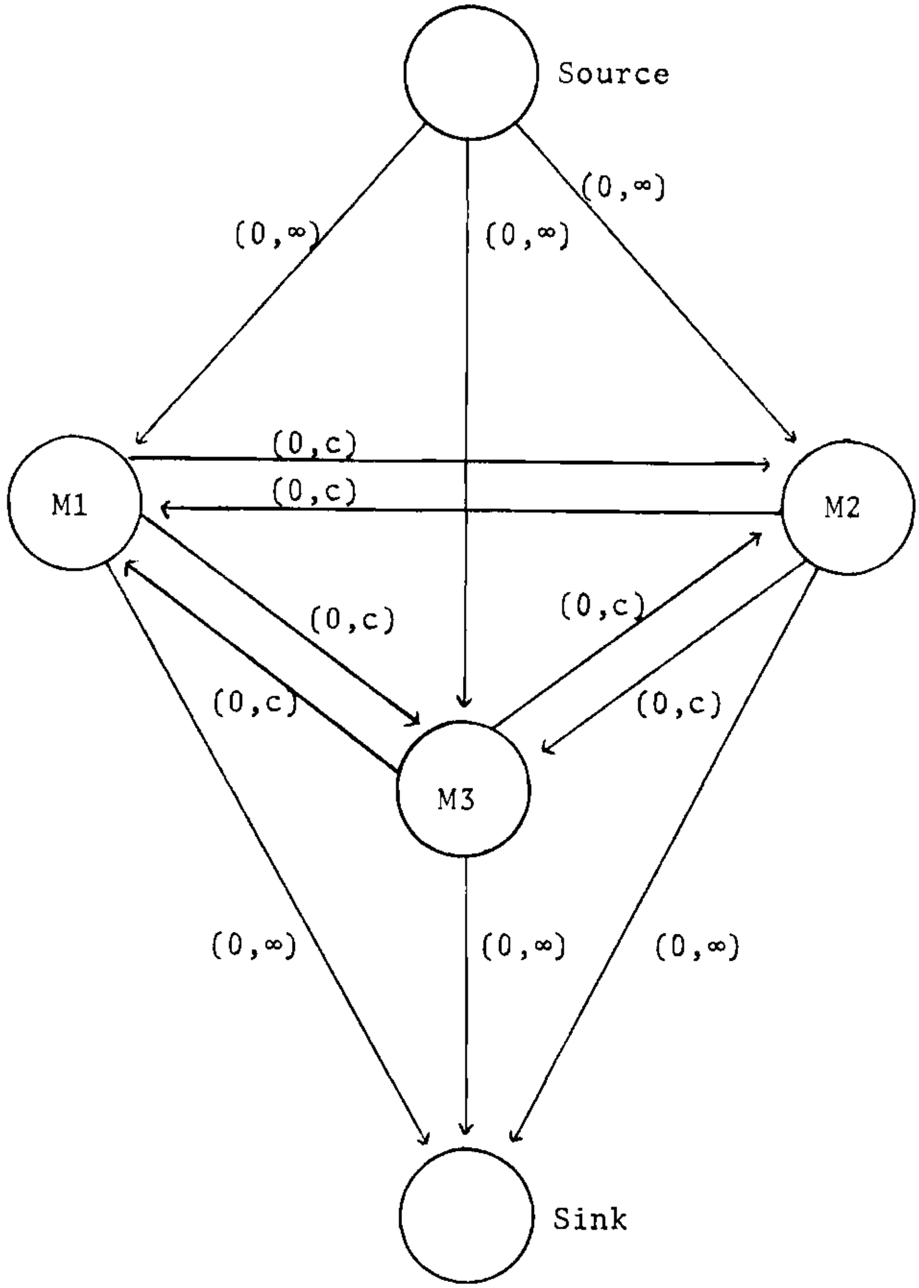

Figure 1. A Job Shop Network Diagram

arrived in a continuous stream with the arrival process being random. The static case where all jobs arrive together for processing has been studied by others. To summarize the process for the jobs in this shop: The job has a predetermined number of operations, a path for the job has been chosen, processing times at each machine are known, and a due date is assigned. Upon release, or loading, each job competes for the available facilities and its path is independent of the sequence required for any other job. That is, these jobs are "engineered" before they are released to the shop for processing.

2.1.2 Assumptions

A real job shop is a relatively complex sociological unit of man and machines, and is usually a key department in the company. Possibly in some companies the shop is so instrumental to the operation that the existence of problems are not apparent to a manager because dysfunctional adjustments are made in other areas to compensate for the shop's shortcomings. As a result, when shop difficulties are overcome, then the other problems surface and need solution. In the age of computers with improved information systems and advancement in the techniques of operation research and management science, much of the slack has been taken from production systems and excesses in inventory, thereby necessitating better decisions in scheduling the shop production.

It is really not surprising that researchers have proposed models for their studies that tend to make the shop appear unrealistic. However, even with these simplifying assumptions, there are no complete solutions. A general job shop with N jobs and M machines has $(N!)^M$ different schedules possible. E. H. Bowman [8] claims a linear programming solution to one version of the problem, coupled with an apology that the approach is not a practical one.

The following list of simplifying assumptions apply to this research.

(1) No machine may process more than one operation at a time.

(2) Each operation, once started, must be performed to completion (no preemptive priorities).

(3) Each job, once started, must be performed to completion (no order cancellations).

(4) Each job is an entity; that is, even though the job represents a lot of individual parts, no lot may be processed by more than one machine at a time. This condition rules out assembly operations.

(5) A known, finite time is required to perform each operation and each operation must be completed before any operation which it must precede can begin (no "lap-phasing"). The given operation time includes setup time.

(6) The time intervals for processing are independent

of the order in which the operations are performed. (In particular, setup times are sequence-independent and transportation time between machines is negligible.)

(7) In-process inventory is allowable.

(8) Machines never break down and manpower of uniform ability is always available.

(9) Deadlines (due dates), if they exist, are fixed.

(10) The job routing is given and no alternative routings are permitted.

(11) There is only one of each type of machine (no machine groups).

(12) Each job has a certain number of operations, each of which can be performed by only one machine.

(13) Each job may be processed more than once by a machine.

(14) Each machine in the shop operates independently, and thus each machine is capable of operating at its own maximum rate of output.

2.2 Literature Review

The review presented here will not attempt to cover in depth what has been done in the field of scheduling, but there are several comprehensive reviews that have been written and would suffice for that purpose. In a work by Sisson [59] the methodology of sequencing is discussed. Meller [39] concentrates on the period after 1957 and primarily discussed formulation and solution of scheduling problems which have provided significant contributions to the field. Gere [22] examines heuristics in job shop scheduling in his review. Moore and Wilson [42] review the simulation approaches to the job shop problem, covering the period after 1957. Detailed coverage of scheduling theory can be found in a book by Conway, Maxwell, and Miller [15], and a book by Ashour [3] is another comprehensive source.

The literature search has revealed a list of more than 200 articles that cover the range of scheduling theory and its application. However, since most of them deal with specific sequencing problems vis a vis the general problem, only a limited number will be mentioned in order to provide an overall understanding of the field.

There are several ways that the literature could be classified.

(1) According to criterion

 (a) job oriented

 (b) shop oriented

(2) According to arrival pattern

 (a) static--all jobs available at time zero

 (b) dynamic--jobs arrive in a continuum stream and according to a specified distribution, in this case, poisson or random

(3) According to job routing

 (a) flow shop--all jobs have same route through the shop (a special case is the assembly line)

(b) job shop--jobs have completely random route through the shop (sometimes called pure job shop)

(c) mixed shop--jobs have nonidentical routes through the shop, but each route is not equally likely.

(4) According to number of machines

(a) one machine in the shop

(b) two machines in the shop

(c) three or more machines in the shop

(5) According to the methodology

(a) analytical approaches

(b) simulation approaches

Here the literature will be classified according to methodology.

2.2.1 Analytical Models

The analytical flow models and analytical job shop models are primarily dynamic programming, branch and bound, algebraic, integer programming, enumeration, queueing and graph theoretic. Johnson [33] provided work in minimizing the maximum flow time for a job in a two machine shop. This is also termed the make span for a job. The shortest processing time (SPT) decision rules provides the optimum results. Smith [60] shows that jobs sequenced in order of nondecreasing processing times also optimizes the one machine case when the criteria is make span. The SPT rule (Conway, [15]) has also been found to minimize average completion time, average number of jobs in process, average waiting time and mean of lateness distribution. These results are of no surprise since

Little [35] provided the rigorous proof that the mean number of jobs in the system is equal to the product of the mean time between arrivals of two consecutive jobs and the mean time spent in the system by a job. Mitten [41] showed that SPT also minimizes the two machine flow shop with lag, i.e. when there is required time between the completion of processing on one machine and beginning of processing on the next machine. Other work with make span as the criterion is presented by Smith and Dudek [59] in which they have developed a generalized algorithm for optimizing a flow shop with no passing.

The initial work dealing with a branch and bound technique for scheduling is credited to Ignall and Schrage [25]. They worked with flow shop models and provided algorithms for solving three machine problems using job related criteria. Lomnicki [36] found an exact solution to the three machine problems using branch and bound techniques with make span as the performance measure. Brooks and White [9] have also done work in the generalized job shop with branch and bound approaches.

Ashour [3] has provided results in branch and bound approaches, graph-theoretic approaches, decomposition techniques, and other analytic approaches. Similarly, Conway [15] has provided many analytic solution procedures for static and dynamic shops in both the restricted flow shop and the general job shop. Johnson [33] and Bellman [7] have solved the two machine flow shop with no due dates using the criterion of minimizing the total time to process all jobs. Johnson has shown theoretically that the optimum case will occur as an extension of the two machine procedure although the optimizing algorithm for three machines has not been found. He further demonstrated that the procedure does not extend to the four machine case. Bellman [7] has approximated the discrete sequencing problem with continuous functions and says, "the importance of my result is that it shows that the three stage dynamic programming process presents a genuinely difficult problem."

Bowman [8] has modeled the problem for solution by linear programming techniques and claims to have solved the problem, although the solution technique is not practical for application. Wagner [65] and Manne [37] have used integer linear programming techniques with job oriented criteria, but like Bowman, the methods are computatively prohibitive for realistic problems.

Some results are available on the analytical work done in approaching the job shop as a network of queues. Burke [10] presents his initial work on queues and proves the intuitive conjecture as stated by Morse [40] that the efflux (output) from a single-channel, exponential service channel, fed by poisson arrivals, must be poisson with the same rate of arrivals. Jackson [29] generalizes these results for a network of queues. He states that when the following assumptions hold, then the machine centers are independent. Jackson's assumptions are:

(1) Jobs are assigned to machines M on a first come-first served basis.

(2) Arrivals from outside the shop are in a poisson type time series.

(3) A job leaving one machine center goes to another or is finished according to a probability distribution associated with the center it is leaving.

(4) Process times are exponentially distributed.
This means that the job shop acts like a collection of independent waiting lines. Jackson [28], as an extension to the above work, provides the equilibrium joint probability distribution of queue lengths for a broad class of queueing-theoretical models representing multi-purpose production systems.

Weber [66] gives the exact steady state solution for a two machine flow shop with unlimited queue length and attempts to extend the procedure to the three machine case. However, he found that adding a unit of capacity to any queue changed the relationship between the previously existing probabilities so that no general expression of the solution could be written. However, given the capacities of all the queues, then a solution could be found using the same procedure. This finding has impact in this research in that it provides sufficient grounds for the adoption of the simulation approach. By extending Weber's work to this system, it can be deduced that no general solution exists. Actually, this is evident since the queue lengths fluctuate with time, and only probablistic statements can be made about their length. Weber's work also adds credence to Jackson's usage of simulation as "experimental mathematics." Chesborough [11] discusses the output of queueing systems considering single server systems, tandem systems, and tandem systems with feedback. Conway [15] states, "a harsh critic could conclude that there are no network queueing results."

2.2.2 Simulation Models

The simulation of the operation of a job shop has added new dimensions to the realism of the models being studied. Managers are usually not willing to have a controlled experiment conducted with their shop, but they have at least allowed the study of the operation to ascertain representative time distributions. The time distributions are then used to model the shops mathematically, and then with simulation. Simulation has proved to be a very effective technique for studying the dynamic shop. Primarily in these studies, the objective has been to analyze the response of various job oriented performance criteria to different local dispatching rules. Sisson [57] reviews the early work in simulation, while Moore and Wilson [42] comprehensively summarize the results of many digital simulation experiments seeking principles of scheduling design valid for job shops. They report that the most encouraging aspect of the simulations to date is that their findings are consistent.

Baker and Dzielinski [4] and Jackson [30] made some of the early attempts at simulating the job shop. Others making early contributions were Nanot [44] and LeGrande [34]. Nanot was careful in designing his experiment with respect to the time series analysis of his data, whereas the statistical validity of LeGrande's work may be suspect. An idea by Ackerman [1] was that jobs spend most of their actual shop time in queue, rather than in processing. Therefore, attention needs to be given to the number of queues a job has to enter. He developed even-flow which is a method for reducing lateness in job shops. Trilling [63] developed a shop simulator for networks and considered assemblies and disassemblies which is a relaxation of one of the normal assumptions.

Gere [22] has done work with a simulator that not only has incorporated the traditional priority dispatching rules, but additionally has considered several heuristics or rules of thumb that add another dimension of realism, as well as to provide improvement. Pettit [49] contrasts the usage of simulation as a study tool to its use for operational production scheduling. Nelson [48] has developed an interactive scheduling model incorporating heuristics for the due-date problem in a realistic shop. The program allows a human scheduler to interact with the model to improve schedules and modify the problems descriptions in an attempt to arrive at a satisfactory solution. Schwartz and Schriber [53] present a "state of the art" paper illustrating their approach to the scheduling problem with GPSS/360. The paper includes logic flow charts and a program listing to demonstrate the compactness of the model in comparison to others.

Undoubtedly the most extensive experimental work with simulation has been done by Conway [13,14,15]. Conway has considered many dispatching rules and their interaction with numerous performance criteria. This investigation was conducted under various shop sizes, flow patterns, work in process levels, and other variable parameters. His work is considered the benchmark to many studies and as such, comparison to his work is made as a step in model validation.

Deane [16] developed a machine oriented performance criterion to measure the deviation of machine utilization from its mean during each period. Additionally, he tested a shop oriented balance measure that is based on variation of the overall shop utilization. Coupled with these job independent criteria, he developed a new dispatching methodology which is a periodic search procedure that guides work to underloaded machines. This means that jobs that can make the largest contributions toward reestablishing work-load balance at underloaded machines are given high priorities in their present operation. This dispatching methodology is dynamic since any job moved ahead in priority has an effect in the selection of future jobs. Using this dispatching methodology and the machine balance criteria, Deane was able to show significant improvement in his results. Essentially Deane administered a controlling mechanism to the flow of a shop that has an uncontrolled random arrival process.

Irastorza [26] developed a loading and balancing methodology for job shop control. He used Deane's model as a starting point and modified it to incorporate a pool of jobs prior to release into the shop. Then, by employing a linear approximation for a mixed integer problem, he developed an algorithm to decide which jobs to load into the shop from the pool. His control methodology to the random arrival process resulted in significant improvement to balance criteria, job related criteria, and to work in process criteria.

In searching the literature for relevant research, there were no studies found that directly investigated measures of network parameters and how they varied across the dispatching rules. Hence, this research is unique in that the purpose is to ascertain which existing dispatching rules can be used to enhance the effectiveness of the network measures and afford the shop manager with another capability of controlling his production runs.

CHAPTER III

PERFORMANCE MEASURES AND DISPATCHING RULES

3.1 General

In a production shop, an objective of planning is to integrate the machine capability with the work load in order to enhance the shop's effectiveness, while simultaneously meeting customer desires. The effectiveness is determined by some measure of performance defined in terms of quantifiable criteria, which ultimately is reflected in terms of cost or profit. Performance measures are the objective criteria in the scheduling problem. The measures have traditionally been descriptive of some salient factor of the particular production shop. Therefore, they are varied according to production factors (minimum production time, minimum idle time), economic factors (minimum work in process), or measures relating to job characteristic or function (minimum job lateness, minimum job tardiness). More recently, measures of shop balance (machine workload balance, shop workload balance) have been studied. The rationale is that the shops have been engineered to have a certain machine composition. Then the machines are grouped into centers which are organized so that work will be uniformly distributed over the shop. The balance measures determine the deviation from the planned load at the various centers, and then adjustments to reduce this deviation are made with the dispatching methodology.

This research is investigating yet another class of measurements that is well known, but has not been used in regard to the scheduling problem. This class of measurements (herein referred to as network flow measures) describes in some manner the flow of work, or jobs, through the shop. Primarily then, various dispatching methodologies have been used to enhance these network flow measures. As stated, the purpose of this research has been to identify relevant measures of discrete network flow and to determine the results as all conditions are held constant, except the dispatching rule. Armed with this information, a comparative analysis with the traditional measures and balance measures has been conducted to ascertain the applicability of the network flow measures.

Many dispatching rules were examined for inclusion in the study, but the number of rules is as varied as one's ingenuity to manipulate weighted sums of rules, ratios of rules, and other manners of composition. Therefore, the rules used in this research were limited to those that have been shown to yield satisfactory performance for realistic criteria. That is, they have been used in actual shops, in many studies, and they are not limited in applicability to specific organizations. Thus, the findings of this research will have more generality with regard to the decision rules and will not be limited in scope to an esoteric subset of applications. Specifically, the dispatching rules were the decision variables which were varied while all other conditions were held constant allowing for the collection of the experimental data for the performance criteria. Thus, the changes in the performance criteria were directly attributable to the isolated decision variable.

3.2 Performance Measures

The statistics on three categories of performance measures which were collected in this simulation model will be discussed in this section. A list of the measures used are provided below in Table 1. The definition and mathematical expression for measures 1-15 can be found in Appendix A. The measures which have been called "variance" are misnomered, in that there is no statistical significance of the term. The intent has been to describe the form of the equation used in evaluating the measure.

Shop criteria are measures characterized by their relation to the shop or machines. They have been used as variables in the balance measures discussed below. Additionally, shop utilization is treated as a given parameter in this research. It is a function of the arrival rate and the random number generator with its inherent variation. Two levels of utilization have been examined in the research.

Table 1. A List of the Performance Measures Used in This Research

1. Average Shop Utilization
2. Average Number of Jobs in Shop
3. Average Number of Operations for Jobs in the Shop
4. Average Work (Hours) Done for Jobs in Shop
5. Average Work in Process (Hours)
6. Time Spent in the System
7. Time Spent in the Shop
8. Average Job Tardiness
9. Variance on Job Tardiness, Average
10. Average Lateness
11. Variance of Lateness, Average
12. Machine Balance Measure
13. Shop Balance Measure
14. Queue Workload Balance
15. Period Queue Balance
16. Variance of Waiting Time Per Operation, Average
17. Average Queue Length in Number of Jobs (Shop)
18. Variance of Queue Length in Hours of Work, Average (Machine)
19. Variance of Interarrival Times, Average (Machine)
20. Variance of Interarrival Times (Shop)
21. Variance of Work Arrived Per Period, Average (Machine)
22. Variance of Work Arrived Per Period (Shop)
23. Variance of Output, Average Machine
24. Variance of Output (Shop)

Measures two through eleven are the traditional measures used in this research. They consist of two broad classes of measures, those being work-in-process and due date criteria. These measures are related to job attributes, i.e., they are characterized by their relation to jobs. These job related measures will distinguish between the jobs and are related to their position in the sequence.

These traditional measures are particularly significant to management because when jobs are failing to meet the due date criteria, then higher costs ensue. These costs take the form of customer dissatisfaction, contract penalty costs, manager and executive time being used up in telephone calls, expediting and extra correspondence, and possibly special production runs which means additional set up cost and improper, inefficient use of the shop, equipment and manpower. However, to meet the due date criteria all the time, the in process inventory criteria must be maintained at higher levels. Clearly, what is needed and typically desired is a balance or trade off between the two classes. Without the balance, inventory holding costs will be high, possibly even necessitating additional warehouse space. In instances where the shop's objective is to repair items that bring the revenue into the company, the higher the in waiting inventory, the less revenue can be produced.

There are relationships between the various traditional measures and they are explained in detail in Conway [15] and

Ashour [3]. Some of these relationships are briefly discussed below. Any dispatching rule that minimizes flow time will maximize utilization. The mean number of jobs in the shop is directly proportional to the mean flow time for a given schedule period. Other relationships from the measures above are that the lateness for job k is equal to the difference in completion time and the due date. Also, lateness for job k is defined as the difference in flow time and allowance time where allowance time for job k is equal to the difference in due date and release time. The mean value of each of these is given by dividing by the number of jobs. Further, we know that completion time of job k is defined as the sum of release time, processing time, and waiting time. From a little algebraic manipulation then we see that lateness is also defined as the sum of all processing time and waiting time minus the allowed time. Now, mean release time, mean due date, mean allowance time, and mean processing time are known and constant after the simulation so that any schedule that is optimal with respect to lateness is also optimal with respect to due date, flow time, and waiting time. In fact, Conway [15] says that if the set of waiting times for machine i and job k is known, then the schedule is completely specified and that the goodness of any schedule is completely a consequence of the values of the waiting times.

Four balance measures, numbered 12 through 15, have also been collected for evaluation in this research. The effect of "balancing" the shop on the traditional performance measures has been studied by Deane [15] and Irastorza [24]. Shop or machine balance measures are based on the fact that shops are designed with a certain machine mix and capacity and should operate most efficiently when these conditions are satisfied. Thus, these measures will measure the deviation either from planned machine or scheduled period workload. According to Irastorza, these measures do not allow compensation or negation between overloaded or underloaded machines, shop or time period. Primarily, the balance measures concerned with time periods are when shop utilization is predictable. There is no one best balance measure, but as with the traditional measures, the determination of which ones to use is dictated by the shop, product, or management policy.

The Machine Balance Index is the average variance of the machine utilization over time. The index is of primary use when it is significant to consider the utilization or work contribution at individual machines or work centers. If it is used to maintain balance, the measure will not allow under utilization on one machine in a time period to compensate for the over production of another machine in the previous period. This measure can best be utilized where there are several machines at a work center to insure there is no labor wasted by partial utilization of a machine group.

The Shop Balance Measure is the variance of work done in the shop taken over the schedule time. One might desire to use this measure if there is diversification in the type work that each worker can do. Thus, in a shop with a great deal of flexibility, a given job can be moved from one machine to another without incurring a big penalty. Therefore, the significance is that the work be distributed evenly over the machines or work force for a given period.

The Queue Workload Balance Index is the variance in the number of jobs at each machine over time. When a shop lacks the flexibility in the assignment of job operations to machines, then this measure could be used. Another instance when this is more desirable is when stability is important for the amount of work in process during a schedule period.

The Period Queue Balance Index is the variance of queue length in number of jobs for all machines over time. This measure is similar to the Queue Workload Balance Index, but it takes into account the variation of the load to the shop over the scheduling horizon.

The remaining measures studied here, numbers 16 through 24, have been termed network flow measures. They were designed to measure some aspect of the system or flow of jobs through the system. With the exception of variance of the waiting time per operation, there is little evidence in the literature of these measures being used as objective criteria for production shop. Since these measures reflect system operation conditions without direct concern with job attributes or management policy, they have been studied to examine their interaction with the dispatching rules.

The definitions and mathematical expressions for the network flow measures are given below. These definitions and expressions are numbered to be consistent with Table 1. The notation where not clear from the context can be found in Appendix A.

16. Variance of the Waiting Time Per Operation--The average waiting time per operation for each machine is calculated first and then the variance of the waiting time for each machine is calculated. An overall average for the variance is then calculated.

$$\overline{W}_i = \frac{1}{a} \sum_{i=1}^{a} W_{i,1}$$

$$\sigma^2_{wi} = \frac{1}{a-1} \sum_{i=1}^{a} (W_{i,1} - \overline{W}_i)^2$$

$$\sigma_w{}^2 = \frac{1}{m} \sum_{i=1}^{m} \sigma^2_{wi}$$

17. Average Queue Length in Number of Jobs--This is the ratio of the sum of the queue length in number of jobs over all machines and all periods to the product of the number of machines and number of periods.

$$\bar{I} = \frac{1}{mp} \sum_{i=1}^{m} \sum_{j=1}^{p} l_{ij}$$

18. Variance of Queue Length in Hours of Work--This is the ratio of the sum over every instant of time of the work in queue to the total time. The "variance" of queue length in hours is determined for each machine and then an overall average is calculated.

$$\bar{w}_i'(t) = \frac{1}{t} \int_o^t w_i'(t)dt$$

$$\sigma_{wi}^2 = \frac{1}{t} \int_o^t [w_i'(t)-w_i'(t)]^2 dt$$

$$\sigma_{w'}^2 = \frac{1}{m} \sum_{i=1}^{m} \sigma_{w_i'}^2$$

19. Variance of Interarrival Time, Average for Machine i--This is the ratio of the sum over all jobs of the difference in time between this arrival and the previous arrival, to the number of jobs processed on machine i. The "variance" for the interarrival time of machine i is calculated and then averaged over all machines.

$$\bar{b}_i = \frac{1}{n_i} \sum_{k=1}^{n_i} (b_{i,k}-b_{i,k-1})$$

$$\sigma_{bi}^2 = \frac{1}{n_i - 1} \sum_{k=1}^{n_i} (b_{i,k} - \bar{b}_i)^2$$

$$\bar{\sigma}_{bi}^2 = \frac{1}{m} \sum_{i=1}^{m} \sigma_{bi}^2$$

20. Variance of Interarrival Time--The average interarrival time for each machine in the shop is calculated. The "variance" of the interarrival time is then determined.

$$\bar{b}' = \frac{1}{mn} \sum_{i=1}^{m} \sum_{k=1}^{n} b_{i,k}$$

$$\sigma_{b'}^2 = \frac{1}{(m-1)(n-1)} \sum_{i=1}^{m} \sum_{k=1}^{n} (b_{i,k} - \bar{b}')^2$$

21. Variance of Work Arrived Per Period, Average for Machine i--This is the ratio of the work arrived to machine i in period j, to all the periods. The "variance" of the work arrived is next found for each machine and then an overall average variance for a machine is calculated.

$$w_i' = \frac{1}{p} \sum_{j=1}^{p} w_{i,j}'$$

$$\sigma_{wi}^2 = \frac{1}{p-1} \sum_{j=1}^{p} (w_{ij}' - \bar{w}_i')^2$$

$$\sigma^2_{w'_i} = \frac{1}{m} \sum_{i=1}^{m} \sigma^2 w'_i$$

22. Variance of Work Arrived Per Period for the Shop--This is the average of the work arrived per period to the shop over all machine and periods. The variance of the work arrived to the shop is then calculated.

$$\overline{w}' = \frac{1}{p} \sum_{i=1}^{m} \sum_{j=1}^{p} w'_{i,j}$$

$$\sigma^2_{w'} = \frac{1}{p-1} \sum_{i=1}^{m} \sum_{j=1}^{p} (\overline{w}_{i,j} - \overline{w}')^2$$

23. Variance of the Output Per Period, Average for Machine i--This is the ratio of the sum of the output for machine i over all periods to the total number of periods. The variance of the output for machine i is calculated and then all machine variances are averaged.

$$\overline{E}_i = \frac{1}{p} \sum_{j=1}^{p} e_{ij}$$

$$\sigma^2_{E_i} = \frac{1}{p-1} \sum_{j=1}^{p} (e_{i,j} - \overline{E}_j)^2$$

$$\sigma_{E_i}^{22} = \frac{1}{m} \sum_{i=1}^{m} \sigma^2_{E_i}$$

24. Variance of the Output Per Period for the Shop-- This is the output of all machines per period summed over all periods and divided by the number of periods. The variance of the shop output per period is the calculation.

$$\overline{E} = \frac{1}{p} \sum_{j=1}^{p} e_j$$

$$\sigma_E^{\ 2} = \frac{1}{p-1} \sum_{j=1}^{p} (e_j - \overline{E})^2$$

Average queue length in number of jobs was selected as a criterion because of the relationship proved by Little [35], see Chapter II. Similarly, the average queue length in hours of work was selected as a network criterion with the rationale that processing times for the operations vary and thus, more information might be gained by using the hours of work, rather than the number of jobs. The measures of the variance of interarrival times were selected because they were thought to be good indicators of smooth flow in the network. Similarly, the variance of the work arrived per period to the shop was hypothesized to be an indication of a constant flow of work over a scheduling period. The variance of output measures are also used to determine a steady flow of work through the machine centers and the shop.

Analyses have also been conducted to determine if there is the same information content in the network flow measures as in those previously used, and whether they could be substituted for the traditional measures or balance measure in order to reach the same conclusions. Also, the ranking of the decision rules across each class of measures has been determined and studies done to determine the agreement or disagreement in classes of measurement.

3.3 Dispatching Rules

The dispatching rules were the independent variable in this research. The purpose, as stated, has been to study the interaction of the performance criteria with the dispatching rules. Since the dispatching rule is the principle method of controlling the flow of jobs through the shop, the relationship of each measure across the rules had to be known. Once the ranking of the rules was determined, then for a particular measure achieving a good schedule for these rules is simply to apply the rules in rank order. However, for multiple criteria or across classes of criteria, the ranking of the rules has not been known previously.

Dispatching rules are classified according to their transient characteristics and the breadth of the information required to employ them. A static rule is one in which the jobs are not selected over time, i.e., once the job order has been determined it does not change. A dynamic rule, on the other hand, does change as a function of time, but as imagined, it requires information about jobs competing for service at a particular machine. A global rule requires information about other machine centers and waiting lines. Clearly, local rules are easier to implement and usually cost less to use because less information is required.

The number of dispatching rules is unlimited and left to one's ingenuity and cleverness. A list of the most commonly used rules in simulation studies is provided by Moore and Wilson [42]. Appendix B gives those rules.

The dispatching rules used in this study are defined below with Table 2 showing the relationship among the rules.

(1) Dynamic Slack (DS)--The job priority is determined by selecting the job that has the least time remaining for the due date, minus all remaining processing time.

(2) Dynamic Slack Per Operation (DSOP)--The job priority is determined by selecting the minimum of the ratio of dynamic slack remaining to the number of operations remaining.

(3) Expected Work in Next Queue (EWIQ)--The job priority is determined by selecting the job that has the minimum sum of the imminent operation processing times of the other jobs in the queue that this job will enter. The queue is considered to include jobs now on other machines that will arrive before the subject job.

(4) Shortest Processing Time (SPT)--The job priority is determined by selecting the job with the least amount of processing time for the imminent operation.

Table 2. Dispatching Rule Relationships

	Static	Dynamic
Local	First Come, First Served	Dynamic Slack
	Shortest Processing Time	Dynamic Slack Per Remaining Operation
	Due Date	
Global	Expected Work in Next Queue	**Dynamic Slack Among All Imminent Jobs

**Not used in this research--illustrative only

(5) Due Date (DD)--The job priority is determined by selecting the job with the earliest due date.

(6) First Come, First Served (FCFS)--The job priority is determined by selecting the minimum of the time the jobs enter the machine queue.

There is no known dispatching rule that gives optimal, or even good schedules, across all performance criteria for the general job shop. This is certainly understandable since criteria have antithetical characteristics, such as dispatching rules do. An example for criteria is the inverse relationship between due dates and work in process levels. An example for dispatching rules is first come, first serve versus last come, first serve. However, there are some performance criteria for specific job shops for which the best dispatching rule is known. Many of these results were mentioned in the literature survey, but they will be reiterated now in the context of this chapter.

With regard to scheduling problems where there is a limit to the size in either number of jobs or number of machines, or where there is some restriction to the flow throughout the shop, then sequencing by the shortest processing time rule has given optimal results for several criteria, and at least good results for others. Specifically, for the n job, 1 machine problem, SPT is known to minimize total completion time, average completion time, average number of jobs in process, variance of the number of jobs in the shop, average waiting time, and average lateness. For the n job, 2 machine case, SPT will minimize the make span with or without lag. In the case of the n job, 3 machine flow shop with make span as the criterion, SPT will give the optimal results. For the n job, m machine flow shop, again SPT will minimize both make span and idle time on last facility. As SPT was used by Conway [13,14,15], Nanot [44], LeGrande [34], Dzielinski [4], and Nelson [48] in simulation experiments, the efficacy of SPT was demonstrated in the general job shop model. Conway [15] devoted one entire experiment to SPT characteristics and capabilities.

The other rules do not have as many results reported, but their worth for some criteria is known. First come, first serve has been shown to minimize the variance of the flow time and waiting time in experiments by Conway [13,14,15], Nelson [48], and Nanot [44]. Conway and Nanot showed that FCFS was better than SPT above the .95 fractile for the flow time distribution. Conway has also employed the SPT and FCFS rules in linear combination and switching between the two, and has shown good results with the flow time distribution. Jackson's [29] network decomposition principle is applicable to the FCFS rule.

In the Conway and LeGrande work, the variance of the completion distribution has been minimized by dynamic slack per operation rule in combination with SPT, but DSOP alone gave good results. Conway has also found that DSOP gives good results in minimizing the number of jobs with positive lateness.

For the one machine problem with minimizing the maximum tardiness, sequencing by ordering the jobs by due dates has given superior results. Gere [22] tested conjectures about the effectiveness of dispatching rules for the same measure of performance. He considers all rules that are functions of the job file as scheduling rules (e.g. DS, DSOP, SPT, DD, EWIQ) whereas all rules that are not functions of the job file are merely priority rules (e.g. FCFS). Gere's results of interest to this research are given below:

Conjecture 1: A scheduling rule whose priority function is not a function of the job file is no more effective than a purely random rule. The results were not conclusive, but FCFS performed better than purely random, although not significantly.

Conjecture 3: (a) If several jobs have different numbers of operations, job slack per operation is more effective than job slack. Job slack was somewhat better than job slack per operation, but there was a small sample. (b) Otherwise, job slack per operation is not less effective than job slack. With the same number of operations, both rules performed equally well.

Conjecture 4: If the jobs have different due dates, a job slack ratio rule (job slack hours divided by hours remaining until due date) is more effective than job slack per operation. The conjecture was refuted.

Conjecture 6: (b) The shortest imminent operation rules (length of next operation) is less effective than job slack for the dynamic problem. The conjecture was supported, job slack was significantly more effective.

Conjecture 9: The look ahead heuristic is effective (look ahead to determine if any jobs are critical with respect to due date). The conjecture was supported.

Other results are reported, but it is not intended to present a comprehensive survey of the known results. Rather, the intent has been to familiarize the reader with the capabilities of the rules in conjunction with a few performance measures. This research will give one a much broader look at six common rules with many criteria.

CHAPTER IV

DESCRIPTION OF THE SIMULATION MODEL, THE VALIDATION PROCESS, AND DESIGN OF THE EXPERIMENT

4.1 General

The simulation model used in this experiment was originally designed, written, tested, and used by Deane [16] to study the workload balance measures and to develop his flow controlled scheduling methodology which enhances these measures. Irastorza [26] extensively modified this model to incorporate the job pool concept coupled with a linear approximation to a mixed integer programming algorithm for loading the shop from this pool. He was able to show improvement in both the workload balance measures and the traditional measures. As explained in Chapter I, these two experiments prompted this research. Since the determination of the cause for improvement is of the essence, the same model used by Irastorza was used here with only slight modification. These modifications dealt only with the collection of the data, and not with the operation and logic of the model.

The process for authenticating the model for this research was a time consuming, but relatively easy task. Once the model was successfully running, the problem was reduced to identifying and setting the variable conditions and the random number seeds used by Irastorza to produce his results. With this accomplished, the output, including the same random number series, duplicated exactly the output found in the dissertation [26].

Although the task of model verification and validation was simplified for this thesis, the model actually underwent quite extensive scrutiny to insure its adequacy. These results will be highlighted in the following sections.

4.2 Description of the Simulation Model

4.2.1 Concept of a Job Pool

In most job shop studies, the jobs are engineered and are sent to the first machine in their sequence as soon as they arrive in the shop. This causes undue length and fluctuation of the queues at the machine centers as well as high work in process levels. However, it has been found that in actual shops in several industries that the shop is not loaded with every job that becomes available. Some jobs are held back whenever they cannot immediately contribute to the improvement of the shop, and subsequently released to the shop whenever it is beneficial. This serves to keep backlogs off the factory floor, balance the workload throughout the shop, keep work in process at lower levels, and speed jobs through the shop, although additional time is spent in this holding area.

Over extended periods of time the amount of work arriving to the shop cannot exceed the capacity of the shop or stochastically there would be an "explosion"; that is, the queue lengths at the machine centers would move to infinity. But over short periods of time the total work arriving may well exceed the capacity and disrupt the smooth, balanced operation. A method to prevent this disruption is the job pool developed by Irastorza [26]. Essentially the jobs all enter a pool which is in "front" of the shop and are then loaded into the shop each scheduling period in batches as determined by a loading algorithm. Whenever the due dates are not critical, additional benefit is derived by the increased flexibility in job selection.

Irastorza developed two such loading algorithms, one which uses a linear approximation for a mixed integer program, and another which employs heuristics. The objective of both algorithms is the improvement of shop balance and work in process measures, while operating under due date constraints. This objective is accomplished by minimizing the deviation from the desired total load for each machine center and the actual load. The desired load is set by management and provides control over the production operation.

The mixed integer programming approach has equality constraints based on the current workload at each machine center. The use of positive and negative slack variable for excess and lack of work as compared to the desired load make the constraints equalities. The program then minimizes the sum of these slack variables. An additional term is in the objective function to insure the due date constraints are met. For more control and flexibility other constraints can be used to increase or restrict the amount of work in the shop, at a work center or groups of work centers. The loading algorithm provides an optimal solution for loading the shop with respect to its objective function, but not in a general sense.

The heuristic loading approach loaded jobs from the pool if the first operation made a contribution to the queue of a machine that was underloaded. For example, for any given underloaded machine, jobs for that machine were taken from the pool according to most imminent due date until the machine reached its desired load or there were no more jobs destined for that machine. An optional feature was to continue adding jobs to the shop according to due date until the total shop desired load was reached. This would put some machines beyond their desired load while others remain underloaded because no jobs were available for them in the pool that scheduling period.

4.2.2 Parameter Description

The job shop modeled was of a general nature and did not attempt to mirror a specific shop. The parameters used were in the ranges of those that can be found in many industries and are thus not restrictive in nature. The selection of a ten machine shop was made because it exhibits enough interaction and combinatorial complexity to adequately represent a real world process while being economical with computer time requirements.

The arrival process to the system was poisson and the interarrival distribution has a mean of 1.88 hours, and was truncated at 40 hours. Using the arrival rate and setting the other parameters resulted in "fixing" the shop utilization at approximately 81%. Thus, an average of 4.25 jobs arrived to the shop in an eight hour scheduling period. These same distributions were used in research by Conway [13,14,15], Nanot [44], and Jackson [27,32].

The jobs had an equal chance of starting their processing on any of the ten machines. The remaining operations of the machines were generated with a probability transition matrix such that each machine had an equal probability for the subsequent operation, regardless of which machine they were on during the current operation. This type of machine assignment is characteristic of the pure job shop.

The processing time per operation was generated with a truncated exponential distribution with a mean of 2.48 hours, but no operation was completed in less than one hour or lasted longer than nine hours. The number of operations for a job was generated once a job arrived at the shop. The distribution is shown below in Table 3.

A job due date was assigned to each job as it entered the shop. The due date was determined by adding the current

Table 3. Number of Operation Assignments

Number of Operations	Probability of Occurrence
4	.15
5	.20
6	.30
7	.20
8	.15

time and the work content of the job plus a random number generated from the uniform distribution between 0 and 150.

The foregoing paragraphs have described the parameters of the model. Now the simulation program will be discussed. The model was written in the GASP II language which was developed by Pritsker and Kiviat [50]. This simulation language is a collection of Fortran IV subroutines designed to run discrete event simulations. Because of this design characteristic, it is very appropriate for use in a job shop application. The basic GASP II routine performs those functions of simulation that are independent of a particular problem. The user himself must write the subroutine to model the processes relating to his application. The primary functions handled by the GASP II subroutines are the maintenance of the simulation clock, the handling of independent files, the ranking of elements in the files, the placing and removing of elements from the files, the random variable generation, and the maintenance of the simulation to include the production of summary output. A complete description of the GASP II language is available in [50].

The operation of the job shop simulator is shown in Figure 2. A description of the user programs written for this simulation are given in Appendix C. The Fortran IV list of the subroutines changed for this research are found in Appendix D. For a complete listing of the model, see Irastorza [26], Appendices B, D, and E. Appendix E is a listing of simulation output.

4.3 Model Verification and Validation

The design of the simulation experiment and the validation process conducted by Irastorza will be discussed in this section. The verification of the model is to show that the simulation model operates as the experimenter intends. Validation is to show the agreement between the behavior of the simulation model and a real system. To insure that proper statistical design was employed, there are several books that provide comprehensive tests. These books are by Naylor, Balintify, and Chu [46], Schmidt and Taylor [51], and Tocher [62]. As a guide to complement these books are the works of other researchers, e.g. Deane [16], Conway [15], and Nanot [44], and papers in the

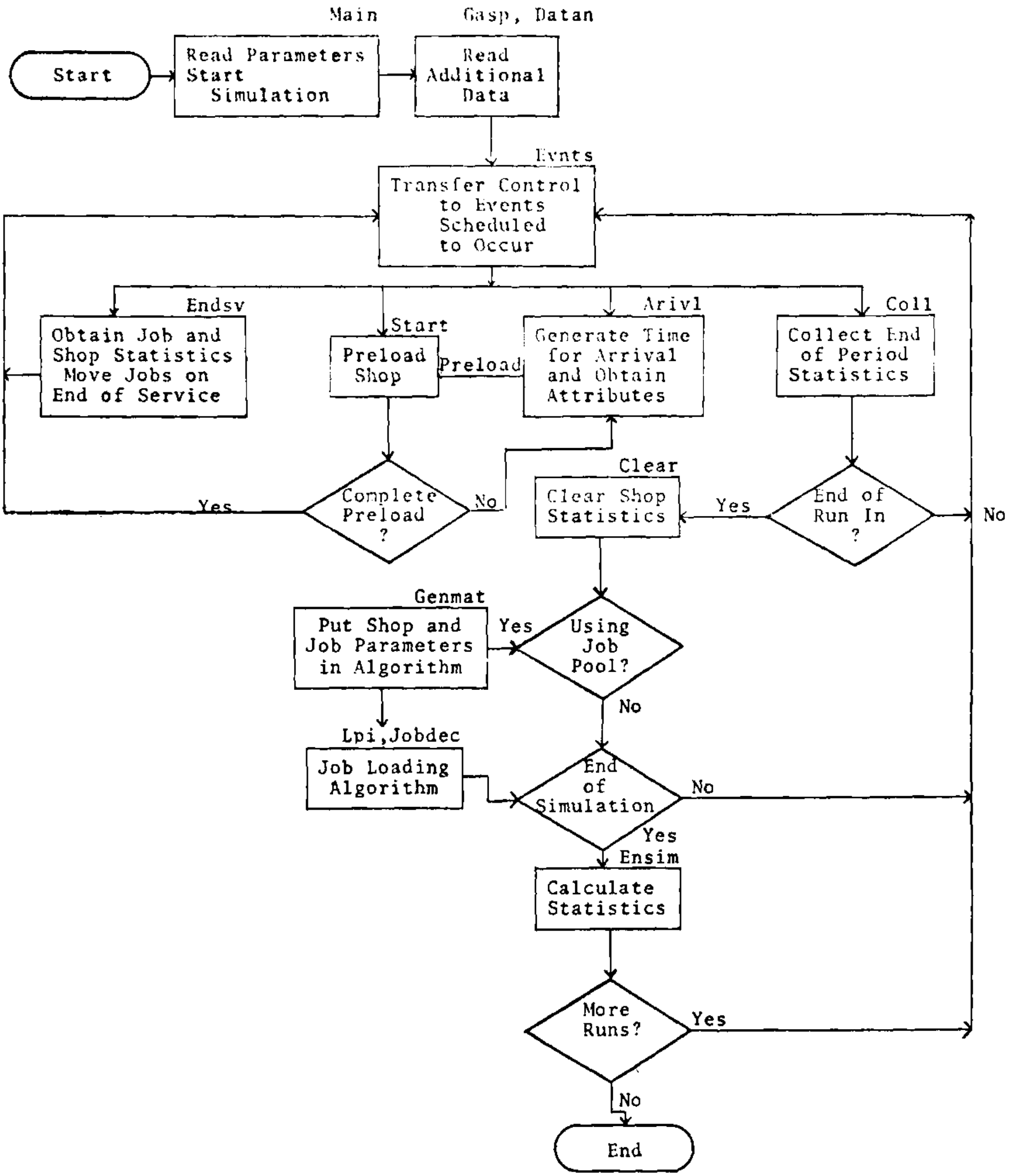

Figure 2. Job Shop Simulator

literature, e.g. Fishman [18] and Van Horn [64].

The problems of primary concern in the verification process include testing the random number generator, starting conditions, run in period, run length, and number of replications.

The random number generator used in this model employs a 17 bit multiplicative congrential method. The general formula is:

$$N_{i+1} = AN_i \pmod{m}$$

where $A = 5^7$ and $m = 2^{17}$

The maximum attainable period with this generator is 32,768. This model needs close to 30,000 random numbers for each run. The random number generator was tested for goodness of fit to a uniform distribution, first order serial correlation, total number of runs, and number of runs of each run length. This research uses 5 of the 12 seeds that passed all of these tests.

The starting conditions are a general consideration for attaining equilibrium and in conjunction with the run in period will render the simulation in steady state. There is no known way to determine good starting condition. Some use the final conditions of a run for the initial conditions while others guess at representative conditions. The closer one comes to the equilibrium state, then the less time required for run in. Nanot [44] cautions against a typical starting condition such as starting with an empty system or starting with the expected equilibrium values. This model preloads the shop with a number of jobs that would give approximately the same number of hours of work in process in the shop as the hours of work in process observed at the end of several trial runs.

The run in period serves two purposes: (1) to render the state probability distribution independent of the starting conditions, (2) to insure the system is stationary before taking statistics. Deane [16] says that without a run in period, the first jobs leaving the system will have biased statistics. The run in period used was 400 hours (50 periods) during which 175 jobs traversed the shop (approximately 1200 operations). This number of hours was determined by comparing the statistics from several runs of different lengths. Also, this number satisfies the rule of thumb (Tocher, [62]) that the operation with the longest cycle be executed three or four times. The longest cycle in this model is the time a job spends in the shop, and as stated, 175 jobs left the shop during the run in period.

The determination of run length is to attain a balance between unnecessary variability in the results and excessive computer run time. Tocher [62] says that the variability associated with the measurements of even very simple simulation models is discouragingly large. However, the analysis that is desired is the relative comparison of results, rather than absolute results. The run length is kept at manageable length by using identical events sequences. The sequence depends only on the seed used in the random number generator and, therefore, is exactly reproducible. This enables the experimenter to reproduce identical conditions to test different alternatives. This is a situation the physical experimenter can only approach and never achieve. A run length of 4000 hours (500 periods) reduced the variance of the measures considerably compared to a run length of 800 hours (100 periods). Longer runs would have required more computer time and it was not justified since a relative analysis was to be made.

The number of replications was determined from a practical point of view, rather than an analytical one. The tradeoffs are the precision desired in the results and the computer time available. Since in this research and the one conducted by Irastorza, the intent is to compare the values of a group of statistics, it was not practical to say that a certain precision was required and then determine the number of runs required to achieve it. Instead, the quantity of five replications was selected as acceptable to both points of view. Another related consideration is whether successive runs should be started with new random number seeds, or whether they should be started with the final calculation of one run as the beginning of the next one. The advantage of the first approach, and the one used here, is a reduced chance of autocorrelation. The second approach eliminates the need for a run in period in the second and succeeding replications as well as providing good starting conditions for each replication after the first one.

The validation process should be one of comparing the results obtained from this model to real shop data. Since this was not possible, it is fortunate that there are other job shop models that have been verified and reported in the literature. The validation for this model was conducted by comparing the results from this model to the results reported by Conway [14] and Deane [16]. The comparative analysis indicated the reasonableness of this job shop model.

A detailed description and test results of the design of the statistical experiment and validation can be found in the dissertation by Irastorza [26].

4.4 Design of the Experiment

The primary purpose of this research has been to investigate the differences in discrete network flow patterns as the dispatching rule changes, and to comparatively analyze the effectiveness of network measures with the traditional measures and the shop balance measures. This experiment was conducted with three different loading approaches to the shop; uncontrolled, pool with mathematical algorithm, and pool with heuristic algorithm. The three different loading approaches provided a capability to isolate the arrival process for investigation. A total of five replications, each dependent upon a different random number sequence, was made for each loading approach using each of the six dispatching rules. A total of 90 runs was required.

For a higher shop utilization, the experiment was conducted with only two loading approaches, uncontrolled and pool with mathematical algorithm. The primary purpose of this portion of the research was to determine the effect of higher utilization on the performance measures; that is, whether or not they deterioriate in capability to measure effectiveness. To accomplish this test, it was necessary first to investigate the differences in network flow as the dispatching rule changed as in the main experiment. A comparative analysis of the performance measure for each class was also made. The due date dispatching was omitted in this segment of the research. A total of 50 runs were necessary for this additional test.

Another determination that was available to be made was the applicability of Jackson's decomposition principle when other than first come, first served queue discipline was used. For answering this question all loading approaches were employed with a different machine and random number sequence for each. Using FCFS the distribution of the interarrival times to the selected machine was tested to insure the data conformed to the negative exponential distribution. With this verified, the other dispatching rules were tested using the same machine and random number sequence.

The statistical hypotheses and the techniques that were used for testing them are discussed below.

(a) To test the null hypothesis that there were no significant differences in dispatching rules, the Kruskal-Wallis nonparametric one-way analysis of variance (ANOVA) by ranks was used. The Kruskal-Wallis test assumes that the variable under study has an underlying continuous distribution. It requires at least ordinal measure of that variable. The test has 95.5% of the power to the parametric ANOVA. The test was applied to each of the performance measures for each loading approach. A total of 120 tests were required for the low and high utilization studies.

(b) To test the null hypothesis that any pair of performance measures did not have the same information content, the nonparametric Spearman rank correlation coefficient was calculated for each pair of measures. Rejection of the null hypothesis determines that the two variables are associated. The technique requires that both variables be measured in at least an ordinal scale so that the variables under study may be ranked in two ordered samples. A total of 828 coefficients were calculated.

(c) To determine the most efficient order of employing the dispatching rules for each measure, the mean value for the five replications were used to rank the dispatching rules. Thus, only a simple ranking was achieved and significant statistical differences were not tested.

(d) To determine the most efficient order for using the dispatching rules for a set of performance measures, a binary comparison procedure for combining multiple sets of ordered data was employed. The comparison of the ordering of a class of performance measures to another class can be made visually from Table 9 in Chapter V.

(e) To test the null hypothesis that the interarrival times to a machine center conforms to an exponential distribution, the Chi-square goodness of fit was used.

(f) To test the null hypothesis that there was no difference in the effectiveness of performance measures at higher levels of utilization than at lower levels, the Spearman rank correlation coefficient was calculated between each criterion at the low utilization with each criterion at the high utilization. A total of 576 coefficients were calculated.

The statistical tests used in this study have been primarily nonparametric. Many of the performance measures studied have dealt with the "variance" of a factor; thus, a normality assumption for the data could not be justified. However, the tradeoff for relinquishing some of the power of the parametric tests is in the generality in which the conclusions can be stated. The procedures for all of the nonparametric tests except the binary comparison procedure are covered comprehensively in Siegel [56] to include a description of the method, the rationale, procedures, an example with small sample size, and an example with large sample size. The binary comparison procedure is explained in [2].

All results from the simulation runs are contained in Appendix F. The next chapter describes the results of the experiment.

CHAPTER V

RESULTS AND ANALYSIS OF THE EXPERIMENT

5.1 General

The results of the computer simulation runs will be discussed in this chapter. The statistical tests performed have been summarized and are presented in tables to provide a complete picture of the relationships found. The most significant results are discussed where appropriate. The chapter has been divided into six sections. The second section discusses the dispatching rule differences and the order for efficient application of the rules for various performance measures. The third section will discuss the analysis of the information content of performance measures and the effect of the loading approach on the measures. The fourth section is devoted to the results of the binary comparison procedure. Section five discusses the results with high utilization. The final section will present the findings pertaining to the Jackson decomposition principle.

5.2 Dispatching Rule Differences and the Order For Efficient Application

To provide the statistical information for testing for the differences in dispatching rules for each performance measure the Kruskal-Wallis ANOVA was applied. The average shop utilization was determined to be of no significant difference, which indicates that the parameter was held constant as intended across the replications and the dispatching rules. For each of the performance measures in each loading approach, the ANOVA was calculated and the results appear in Table 4. In this set of calculations, it was desired to have significant differences and such was the case for all but two of the measures. The variance of interarrival times, average (machine) indicated differences in the dispatching rules for the uncontrolled arrival process, but for the other two loading approaches the results did not indicate sufficient differences. The math pool had a computed "H" of 14.27 compared with the critical value of size .05 of 11.07. But, for size .01, the critical value was 15.09. The pool heuristics approach had still less differences between dispatching rules with a computed "H" of 7.44. The suspected reason for this lack of differences is that the pool will have some effect in smoothing the arrival process to the shop. Since the pool attempts to minimize the deviation between desired workload and actual workload regardless of the inherent fluctuations caused by the dispatching rule, more jobs will be sent to underloaded machine thereby smoothing the interarrival distribution. The variance of interarrival times (shop) was found to have the exact results as the other interarrival time measure, but this is not surprising in view of the way the measures were

Table 4. Kruskal-Wallis "H" Values for Dispatching Rules--Low Utilization

	No Pool	Math Pool	Pool Heuristics
1. Average Shop Utilization	3.94	6.67	5.09
2. Average Number of Jobs in Shop	26.45	26.94	26.84
3. Average Number of Operations For Jobs in the Shop	27.42	26.83	26.94
4. Average Work (Hours) Done for Jobs in Shop	27.42	26.72	26.82
5. Average Work in Process (Hours)	26.71	26.87	26.72
6. Time Spent in the System	26.04	26.75	25.75
7. Time Spent in the Shop	26.04	26.89	26.72
8. Average Job Tardiness	26.03	15.52	26.75
9. Variance of Job Tardiness, Avg.	24.54	20.77	25.38
10. Average Lateness	25.00	26.75	25.67
11. Variance of Lateness, Average	26.41	26.74	26.83
12. Machine Balance Measure	17.82	16.09	12.12
13. Shop Balance Measure	22.16	24.12	23.59
14. Queue Workload Balance	26.09	26.87	25.45
15. Period Queue Balance	18.27	17.15	19.41
16. Variance of Waiting Time Per Operation, Average	24.71	26.80	24.94
17. Average Queue Length in Number of Jobs (Shop)	26.51	27.05	26.86
18. Variance of Queue Length in Hours of Work, Average (Machine)	23.95	18.16	20.76
19. Variance of Interarrival Times, Average (Machine)	18.33	14.27	7.44
20. Variance of Interarrival Times (Shop)	18.35	14.27	7.39
21. Variance of Work Arrived Per Period, Average (Machine)	21.38	23.70	16.09
22. Variance of Work Arrived Per Period (Shop)	24.03	25.39	24.04
23. Variance of Output, Average Machine	16.89	18.69	22.89
24. Variance of Output (Shop)	23.53	24.02	23.64

Critical Values:

$\alpha = .05$ $H = 11.07$

$\alpha = .01$ $H = 15.09$

calculated. (See Chapter III.)

Once it was determined that there were significant differences in the dispatching rules, it was desired to determine the ranking of the rules in order of efficiency for each measure. This was accomplished by using the mean of the five replications with the most efficient rule being listed first. The efficiency ordering of the dispatching rules for each loading approach is in Table 5 and provides direct comparison of the rules across the loading approaches and across the performance measures.

Initially, it is interesting to note that the ordering of shop utilization appears random for different loading mechanisms. For the work in process measures: average number of jobs in the shop (2), average number of operations for jobs in the shop (3), average work done in hours for jobs in the shop (4), average work in process in hours (5), time spent in the system (6), and time spent in the shop (7), there is similarity in the way the dispatching rules should be applied. However, EWIQ is last for measures 3 and 4, whereas for the other work in process criteria it is third. Evidently, EWIQ is fairly effective in lowering the levels of work awaiting processing for early operations on a job, but it is not getting jobs that are nearing completion out of the system. For the due-date measures: average job tardiness (8), variance of job tardiness average (9), average lateness (10), and variance of lateness average (11), three

Table 5. Efficiency Order for the Dispatching Rules; 1-DS, 2-DSOP, 3-EWIQ, 4-SPT, 5-DD, 6-FCFS--Low Utilization

	No Pool	Math Pool	Pool Heuristics
1. Average Shop Utilization	513624	125364	153642
2. Average Number of Jobs in Shop	543162	543612	543162
3. Average Number of Operations for Jobs in the Shop	541263	541263	451263
4. Average Work (Hours) Done for Jobs in Shop	541263	541263	451263
5. Average Work in Process (Hrs)	543126	543162	543162
6. Time Spent in the System	543162	543612	543612
7. Time Spent in the Shop	543162	543612	543162
8. Average Job Tardiness	215436	541236	215436
9. Variance of Job Tardiness, Average	125643	125643	125463
10. Average Lateness	543162	543612	543612
11. Variance of Lateness, Avg.	126543	126543	216543
12. Machine Balance Measure	126453	126453	216435
13. Shop Balance Measure	162453	126453	126453
14. Queue Workload Balance	543162	543612	453162
15. Period Queue Balance	541236	541623	541362
16. Variance of Waiting Time Per Operation, Average	654123	654123	654123
17. Average Queue Length in Number of Jobs (Shop)	543162	543612	543162
18. Variance of Queue Length in Hours of Work, Avg. (Machine)	316254	612345	316245
19. Variance of Interarrival Times, Average (Machine)	162345	162345	613245
20. Variance of Interarrival Times (Shop)	162345	162345	613245
21. Variance of Work Arrived Per Period, Average (Machine)	321654	316245	321654
22. Variance of Work Arrived Per Period (Shop)	126345	126453	126354
23. Variance of Output, Average Machine	541623	451623	456123
24. Variance of Output (Shop)	162354	126453	126453

of the measures 8, 9, 11 would use the dispatching rules in one order for the best results, but measure 10 would do something different for the best results. Measure 10 resembles the ordering encountered in the work in process measures, (2-7). The difference in the ordering for measure 10 is a surprise since there is a direct relationship between tardiness and lateness. Possibly, this difference between measures 8 and 10 can be attributed to the manner in which tardiness is calculated, that is, tardiness is equal to the maximum of zero and lateness. Thus, lateness can range down into the negative numbers whereas tardiness is limited by zero on the lower side and lateness on the upper side. This truncation effect could result in the observed differences. Also, DD attempt to meet all due dates in the shop, enabling lateness to perform well since it is the difference in flow time and allowance time. The dynamic dispatching rules, on the other hand, look for jobs with the least slack and thus, move jobs ahead when their slack becomes critical. Neither of these arguments however, explain why DS is best for the uncontrolled loading and DD is best for the mathematical pool unless one considers that the pool attempts to maintain a desired workload in the shop and meet all due dates. This reasoning is supported by the results with the pool heuristics since it only moves jobs from the pool when a machine center is underloaded, thus enhancing uniformity of network flow. The variance measures, 9 and 11, are inversely related to measure 10 in that dispatching rules that perform well with lateness as the criterion such as SPT, also disturb the smooth flow of the shop operation, creating sporatic work flow and thereby increasing the variability of this measure. This conjecture is supported by the observation that measures 9 and 11 have different rankings than measure 10.

The balance indices: Machine Balance Index (12), Shop Balance Index (13), Queue Workload Balance Index (14), and Period Queue Balance Index (15), provided antithetical results. Measures 12 and 13 would use the dispatching rules in one order and measures 14 and 15 would use nearly the opposite order. The difference between measures 12 and 13 with measures 14 and 15 is easy to understand when one examines the mathematical formulation. The first two measures, 12 and 13, are indices of the work done, implying uniform work flow. Thus, since the work has been accomplished, the queue lengths are short. Measures 14 and 15, on the other hand, are indices of the queue length in number of jobs, and the work to be done is awaiting processing and due dates become more critical. Hence, an inverse relationship can be seen for if the work is in queue, then it could not possibly have been completed and vice versa. Still this inverse relationship was not suspected until this analysis, as it was thought that the balance indices would give substantially the same results.

The network flow measures defined for this research have given mixed results as was anticipated and desired. The network flow measures are: variance of waiting time per operation, average (16), average queue length in number of jobs (17), variance of queue length in hours of work, average (18), variance of interarrival times to a machine, average (19), variance of interarrival times to the shop, average (20), variance of work arrived per period to a machine, average (21), variance of work arrived per period to the shop (22), variance of output for a machine, average (23), and variance of output for the shop (24). Measure 16 is the only measure that uses FCFS first and beyond that, the only measure that has a similar application for the dispatching rules is 23. Measures 17 and 23 are used in about the same order and they correspond to the work in process measures, average lateness, and partially to the balance measures. Measures 18 and 21 are used in about the same order. In fact, they are the only measures that use EWIQ first. There is no apparent correspondence with any other measures.

It is reasonable that the look ahead dispatching rules would perform best with criteria 18 and 21 since they are both oriented to the variance of hours of work at a machine. This rule, by its inherent capability to ascertain the future workloads at the machine centers, will tend to smooth the work flow, thus reducing the variance of hours of work at the machine in the next period. Measures 19, 20, 22, and 24 are very similar in the ordering of the rules and show strong correspondence to the ordering of measures 9, 11, 12, and 13. Measures 19, 20, 22, and 24 are all measures that are indicative of uniform work flow, and since the other measures 9, 11, 12, and 13 have been seen to perform best with dispatching rules that produce uniformity of flow; i.e. the dynamic rules, it is evident that the rankings should be similar.

Now let us reverse the role of the performance criteria and dispatching rules to determine which performance criteria to use, given that a dispatching rule has been selected. For the dynamic rules it has been observed that the uniformity of network flow has been enhanced. Thus, to measure this uniform work flow, the network flow criteria, 19, 20, 22, and 24 would provide good measures of a steady flow. The uniform flow, however, will create higher work in process levels in order to maintain the uniformity. These higher work in process levels would be detrimental to the work in process criteria which attempt to move the work through the shop quickly and at low levels of work in process. Similarly, one could expect due date measures, 8, 9, and 11 to provide good results due to their inverse relationship with the work in process criteria as previously discussed. Balance measures, 12 and 13, also perform well when uniform work flow is important. Where the DD rule is used, possibly because of high penalty costs for late jobs, or if customer satisfaction is paramount, then the work in process criteria have been shown to be good. Again, this is because they are enhanced by fast flow of work through the network which results in highly variable network flow. SPT has been shown to be similar to the DD rule in that this rule moves work through the system rapidly, but at the cost of increasing the variability of network flow. Where FCFS is employed because of its ease of implementation and implicit fairness, the network flow measures which indicate uniformity of processing would perform well as the performance criteria. However, for this rule, the variance of the waiting time has given the best results.

Many criteria can be selected for a given rule with the use of Table 5, not only by using the positive relationships, but also by utilizing antithetical techniques. The foregoing discussion has been primarily intended to interpret the effect of the rules on the flow of work.

The analysis has shown that for the various performance measures, each of the dispatching rules has been best for some of the measures. This fact is of interest in that it corresponds to findings in other studies found in the literature. The only major exception to the results is that SPT is not the best dispatching rule for time spent in the shop, average number of jobs in the shop, average work in process, and average lateness as indicated in Table 5. This can be attributed to the function for the due dates; that is, too much time could have been allowed for the jobs from their release time until their due date. These loose due dates would enable the DD rule to be highly efficient as is demonstrated. For the work in process measures, one would expect the ordering of the rules that has resulted since these measures all attempt to move the work through the shop fast, and at low levels. Recall the discussion in Chapter III about the inverse relationship between work in process and due date criteria; thus, a different order is expected. Even the result that DS would be best in that category is expected because of the manner in which DS operates directly with the due date. The conjectures of Gere listed in Chapter III are also reflected in the results obtained. EWIQ is the better dispatching rule for minimizing the variance in measure 18 and in measure 21, yet measures 14 and 15 that attempt to balance the queue lengths have better results with DD and SPT. This could be attributed to the fact that EWIQ does not attempt to balance. Rather, it selects the job that will move to the queue with the least work. When an order for all measures was determined, except for DD as explained above, the fact that DS was better than SPT again supports a conjecture of Gere's that for the dynamic shop, DS is better than SPT.

5.3 Analysis of the Information Content of the Performance Measures

The primary purpose of this research has been to investigate the differences in discrete network flow patterns under various dispatching methodologies and to identify relevant measures of network flow. This section will focus on the results with regard to the capability of the network flow measures to provide the same information as the traditional measures and the balance indices. The Spearman rank correlation coefficient was used to determine the association of two measures. Since the ordering of the rules was not of primary importance here, all 30 observations for each performance measures for each loading approach was used to compute the coefficients. Two levels of significance were used: for size .01, $r_s = 0.4250$ and for size .001, $r_s = 0.5490$. Both positive and negative correlations were determined. Table 6 contains the results for the uncontrolled loading approach. Table 7 displays the results of the mathematical pool. Table 8 has the results for the pool heuristics. The results of this correlation study coupled with the efficient ordering of the dispatching rules, reveals considerable redundancy in the information content of the performance measures. Each performance measure but one has been found to correlate positively at size .001 across the loading approaches. The one exception was the correlation of the variance of work arrived per period, average (machine).

Table 6. Correlation of Performance Measures--No Pool-Low Utilization

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	P	H
2		⊕	⊕	⊕	⊕	⊕			⊕	⊖	-	-	⊕	⊕		⊕	-	⊖	⊖		⊖	+	⊖	⊕	⊕
3			⊕	⊕	⊕	⊕	+		⊕				⊕	⊕		⊕	⊖			⊖		⊕		⊕	⊕
4				⊕	⊕	⊕	+		⊕				⊕	⊕		⊕	⊖			⊖		⊕		⊕	⊕
5					⊕	⊕			⊕	⊖	-	-	⊕	⊕		⊕	-	⊖	⊖		⊖	+	⊖	⊕	⊕
6						⊕			⊕	⊖	-	-	⊕	⊕		⊕	-	⊖	⊖		⊖	+	⊖	⊕	⊕
7									⊕	⊖	-	-	⊕	⊕		⊕	-	⊖	⊖		⊖	+	⊖	⊕	⊕
8								⊕		⊕	⊕	+									+			⊕	⊕
9										⊕	⊕	⊕									⊕		⊕	⊕	⊕
10										⊖	-	-	⊕	⊕		⊕	-	⊖	⊖		⊖	+	⊖	⊕	⊕
11											⊕	⊕	⊖			⊖		⊕	⊕		⊕		⊕	⊕	⊕
12											⊕	⊖				-		⊕	⊕		⊕		⊕	⊕	⊕
13												⊖				-		⊕	⊕		⊕		⊕	⊕	⊕
14														⊕		⊕		⊖	⊖		⊖		⊖	⊕	⊕
15																⊕	-	⊖	⊖			+	⊖	⊕	⊕
16																	-			⊖		+		⊕	⊕
17																	-	⊖	⊖		⊖	+	⊖	⊕	⊕
18																		+	+	⊕	+	⊖	+	⊕	⊕
19																			⊕	+	⊕		⊕	⊕	⊕
20																				+	⊕		⊕	⊕	⊕
21																						⊖		⊕	⊕
22																							⊕	⊕	⊕
23																								⊕	⊕
24																								⊕	⊕

For + or -, $\alpha = .01$

For ⊕ or θ, $\alpha = .001$

P - Math Pool

H - Pool Heuristics

Table 7. Correlation of Performance Measures--Math Pool-Low Utilization

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	N	H
2		⊕	⊕	⊕	⊕	⊕			⊕	⊖	⊖	⊖	⊕	⊕		⊕	-	⊖	⊖	-	⊖	+	⊖	⊕	⊕
3			⊕	⊕	+	⊕	⊕	+	+				+	⊕	+	⊕				⊖		⊕		⊕	⊕
4				⊕	+	⊕	⊕		+				+	⊕	+	⊕				⊖		⊕		⊕	⊕
5					⊕	⊕			⊕	⊖	⊖	⊖	⊕	⊕		⊕	-	⊖	⊖	-	⊖	+	⊖	⊕	⊕
6						⊕			⊕	⊖	⊖	⊖	⊕	⊕		⊕	⊖	⊖	⊖	-	⊖	+	⊖	⊕	⊕
7									⊕	⊖	⊖	⊖	⊕	⊕		⊕	-	⊖	⊖	-	⊖	+	⊖	⊕	⊕
8								⊕												-				⊕	⊕
9										⊕	+	⊕									⊕		⊕	⊕	⊕
10										⊖	⊖	⊖	⊕	⊕		⊕	⊖	⊖	⊖	-	⊖	+	⊖	⊕	⊕
11											⊕	⊕	⊖			⊖	+	+	+		⊕		⊕	⊕	⊕
12												⊕	⊖			⊖	+	⊕	⊕		⊕		⊕	⊕	⊕
13													⊖			⊖	+	⊕	⊕		⊕		⊕	⊕	⊕
14														⊕		⊕	-	⊖	⊖	-	⊖	+	⊖	⊕	⊕
15																⊕	-	-	-	⊖		⊕		⊕	⊕
16																				-		+		⊕	⊕
17																	-	⊖	⊖	-	⊖	+	⊖	⊕	⊕
18																		+	+	+	+	-	+	⊕	⊕
19																			⊕		⊕		⊕	⊕	⊕
20																				+	⊕		⊕	⊕	⊕
21																						⊖		⊕	+
22																							⊕	⊕	⊕
23																								⊕	⊕
24																								⊕	⊕

For + or -, $\alpha = .01$

For ⊕ or ⊖, $\alpha = .001$

N - No Pool

H - Pool Heuristics

Table 8. Correlation of Performance Measures--Pool Heuristics-Low Utilization

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	N	P
2		⊕	⊕	⊕	⊕	⊕			⊕	θ	θ	θ	⊕	⊕		⊕	θ				θ	+	θ	⊕	⊕
3			⊕	⊕	+	⊕			+				⊕	⊕		⊕	θ			-		⊕		⊕	⊕
4				⊕	+	⊕			+				⊕	⊕		⊕	θ			-		⊕		⊕	⊕
5					⊕	⊕			⊕	θ	θ	θ	⊕	⊕		⊕	θ	-	-		θ	+	θ	⊕	⊕
6						⊕			⊕	θ	-	θ	⊕	⊕		⊕	θ				θ	⊕	θ	⊕	⊕
7									⊕	θ	-	θ	⊕	⊕		⊕	θ				θ	⊕	θ	⊕	⊕
8								⊕		⊕		+									+			⊕	⊕
9										⊕		⊕									⊕		⊕	⊕	⊕
10										θ	-	θ	⊕	⊕		⊕	θ				θ	⊕	θ	⊕	⊕
11											+	⊕	θ	-		θ					⊕		⊕	⊕	⊕
12												⊕	θ	-		-		⊕	⊕		⊕		⊕	⊕	⊕
13													θ	-		θ		⊕	⊕		⊕		⊕	⊕	⊕
14														⊕		⊕	-	-	-		θ	+	θ	⊕	⊕
15																⊕	θ	θ	θ		θ	⊕	-	⊕	⊕
16																				-		+		⊕	⊕
17																	θ				θ	⊕	θ	⊕	⊕
18																				+		θ		⊕	⊕
19																			⊕		+		⊕	⊕	⊕
20																					+		⊕	⊕	⊕
21																						-		⊕	+
22																							⊕	⊕	⊕
23																									
24																									

For + or -, α = .01

For ⊕ or θ, α = .001

N - No Pool

P - Math Pool

Between uncontrolled and the mathematical pool, and uncontrolled and the pool heuristics, the correlation was insignificant at size .001, but the correlation between the mathematical pool and the pool heuristics was only significant at size .007.

As expected, there is a high degree of positive correlation among the work in process measures. For the due date criteria there is high positive correlation in all but average lateness. Average lateness has no significant correlation with the other due date criteria except the variance of the lateness, average and that was negative correlation at a significance of size .001. However, average lateness was found to have high positive correlation with the work in process measures. The balance criteria had high positive correlation between the machine balance measure and the shop balance measure, but each had high negative correlation with the queue workload balance index and no significant association with the period queue balance index. However, the period queue balance index and high positive correlation with the work in process measures and average lateness. The queue workload balance had high positive association with the period queue balance index as well as the work in process criteria and average lateness.

The results with the network flow measures were mixed similar to the results with the dispatching rules. This was expected and the only surprise came with the variance of waiting time per operation, average. Since the mean waiting time criteria was known to be good, the second moment was thought to be good and as such was formulated as a network flow measure. However, it has shown very little association at the significance desired with any of the other measures. The only high correlation computed with this measure was with the variance of the work arrived per period, average for a machine, and it was negative. The next worse network measure was the work arrived per period, average for a machine. It produced high negative correlation with two work in process measures and high positive correlations with variance of the queue length in hours of work, average for a machine. Fortunately, all of the network measures were not that deficient in information content. The average queue length in number of jobs for the shop had high positive correlation with all work in process measures, average lateness, queue workload balance index, and the period queue balance index. The variance of the output, average for a machine had significant correlation with the same measures as the average queue length, but the results were mixed between significance size .01 and size .001. The remaining network flow measures had significant high correlation with part of the work in process measures, due date criteria and balance indices, but the correlations were both positive and negative corresponding in sign, and consistent with the measures previously discussed. This is made readily apparent upon examination of the tables.

5.4 Combining Multiple Sets of Ordered Data With a Binary Comparison Procedure

The solution procedure discussed herein was used by Ford [20] in developing his technique for combining sets of partially ordered data. The binary comparisons procedure is a method for determining a single rank order for the problem in which there is less than perfect agreement by all judges.

A win-loss matrix, A, is computed for each set of M judges and their preferences for N objects. The matrix can be represented as:

$$A = \begin{vmatrix} 0 & a_{12} & a_{13} & \cdots & a_{1N} \\ a_{21} & 0 & a_{23} & \cdots & a_{2N} \\ a_{31} & a_{32} & 0 & \cdots & a_{3N} \\ \vdots & \vdots & \vdots & \vdots & \\ a_{M1} & a_{M2} & A_{M3} & \cdots & 0 \end{vmatrix}$$

In the matrix, a_{ij} represents the number of times object i has been preferred to j. The win-loss percentage for object i is computed as the sum of row i observations divided by the sum of the observations in row i and column i. A computerized program for computing the win-loss matrix was developed by Andrews and Pelz [2] and used in this research. Using this procedure with the program, not only is an overall ranking of the goals provided, but in addition, the relative magnitude of the win-loss percentages provide more insight into how much one object is preferred to another. These percentages are seldom on an equal interval continuum as provided in most scoring models.

To ascertain the composite ordering of the rules for similar groups and also to determine overall ordering for classes of measures, the binary comparison procedure was applied. The composite results show the final rankings for groups of measures and eliminates minor inconsistencies. The results in Table 9 are for groups of measures that have a high degree of similarity in information content and for the known classes of measures. Direct comparison can be made for any measure from Table 5 to the selected groups. Additionally, the win-loss percentage as computed is given from the win-loss matrix which is indicative of the degree of preference between dispatching rules.

The rankings for the work in process measures and criteria from other classes were consolidated in combination 2. The composite ranking was the same for this group as it was for the work in process measures. However, for the

Table 9. Efficiency Ordering of Dispatching Rules with the Win-Loss Percentages

	Criteria Combination	No Pool Order	No Pool Win-Loss %	Math Pool Order	Math Pool Win-Loss %
1	2,3,4,5,6,7	541362	*,*,.778,.667,.278,.278	543162	*,*,.667,.611,.500,.222
2	2,3,4,5,6,7,10, 14,15,17,23	541362	*,*,.788,.667,.303,.242	543162	.982,.818,.382,.364, .345,.109
3	8,9,11	125643	.933,.867,.533,.333, .267,.067	125463	.867,.667,.667,.400, .333,.069
4	8,9,10,11	125463	.800,.650,.650,.400, .300,.200	512463	.750,.700,.500,.500, .350,.200
5	18,19,20,21,22, 24	162354	.900,.667,.633,.600, .100,.100	162345	.933,.733,.633,.367, .267,.067
6	12,13,14,15	154263	.750,.600,.600,.450, .400,.200	154623	.700,.600,.600,.500, .450,.150
7	8,9,11,12,13	126543	.960,.800,.480,.400, .320,.040	125643	.920,.920,.480,.440, .400,.040
8	8,9,11,12,13,19, 20,22,24	126543	.978,.733,.600,.244, .244,.200	126453	.956,.711,.556,.356, .311,.111

*Universally Superior

loading approaches there was a difference in the ranking of EWIQ (3) and DS (1), which is attributable to DS being better than EWIQ, FCFS, and DSOP in the uncontrolled loading approach than in the math pool approach. The win-loss percentage of EWIQ is the same for both loading approaches whereas, DS has a higher win-loss percentage in the uncontrolled approach than in the math pool approach.

For the due date criteria in combination 4, there is a difference in the rankings for the loading approaches. For the uncontrolled loading the DD rule is third, but in the math pool the DD rule is first. Upon examining the individual rankings, one sees that the DD rule was first in three due date measures for the math pool which is caused by the loading algorithm meeting the DD constraints. In the uncontrolled approach, the dynamic rules perform better than the DD rule since the dynamic rules enhance uniformity of flow enabling better performance to be realized for these measures. The win-loss percentages for combination 4 in the math pool are generally lower than without the pool which is indicative of more inconsistencies in individual rankings.

For the workload balance class of criteria the difference in composite ranking is between positions four and five where DSOP and FCFS are interchanged. Similar rationale as used above would explain the differences; however, since the win-loss percentages for these rules is low in both loading approaches neither rule would be suggested for use.

Over all the composite rankings DS has attained the highest win-loss percentage in six of the eight combinations. Even in the other two composite rankings it had a high win-loss percentage although DD and SPT were universally superior. Since this rule will reduce the variability of network flow as well as maintain workload balance and produce good results with the due date criteria it might be the best rule to use for overall shop performance. The work in process levels would probably be a little higher, but DS has also been shown to perform well with those measures. This result with DS supports the conjecture of Gere [22] that the dynamic slack rule will give good performance in the dynamic shop.

5.5 Results of the Experiment with High Utilization

At the high level of shop utilization, the capability of the performance criteria to measure effectiveness is of primary concern. The higher utilization was obtained by increasing the parameter of the interarrival time distribution from .53 to .60, and resulted in a utilization of approximately 91%. Additionally, the desired management load factor for the job pool was increased from 4.25 to 6.00, which enables a more realistic evaluation of the process, since the loading algorithm works on the deviation of the actual shop load with the desired shop load. Clearly, the load is increased by the change in the parameter of the interarrival time distribution.

The first test applied to the data was to determine if there was a significant difference across the dispatching rules for each measure in each loading approach. The results of the test are contained in Table 10. There were three measures, 12 and 21, for the uncontrolled loading and 18 for the math pool, that had no difference at size .01. One of them, 12, had no significant difference at size .05. Measure 12 had a computed "H" statistic of 3.64 compared with the critical values of 9.49 for size .05 and 13.28 for size .01. Measure 18 had a computed "H" statistic of 13.09 and measure 21 also had a computed "H" statistic of 13.09. For measure 12, this means that the dispatching rule had little influence on the overall machine average of the deviation of work done on a machine per period to the mean work done over time. For measure 18, the dispatching rules had little effect on the variability of queue length in hours of work, which could be expected, since more work was available to process compared with the same service rate. Measure 23 would suffer because of the same rationale; that is, the variance of the work arrived per period for a machine is higher and less control is realized by the dispatching rule. As previously mentioned, the DD rule was not used in this test. Similar to the main experiment, the ranking of the rules for each criterion in order of efficiency was next done.

Table 10. Kruskal-Wallis 'H' Values for Dispatching Rules--High Utilization

	No Pool	Math Pool
1. Average Shop Utilization	13.35	20.84
2. Average Number of Jobs in Shop	18.70	17.54
3. Average Number of Operations for Jobs in the Shop	18.85	22.24
4. Average Work (Hours) Done for Jobs in Shop	18.60	22.24
5. Average Work in Process (Hours)	17.66	14.94
6. Time Spent in the System	19.59	20.86
7. Time Spent in the Shop	19.59	18.08
8. Average Job Tardiness	20.74	19.81
9. Variance of Job Tardiness, Average	22.56	20.36
10. Average Lateness	19.83	20.77
11. Variance of Lateness, Average	22.16	22.39
12. Machine Balance Measure	3.64	19.28
13. Shop Balance Measure	18.42	17.51
14. Queue Workload Balance	19.41	19.44
15. Period Queue Balance	15.39	12.44
16. Variance of Waiting Time Per Operation, Average	22.16	22.15
17. Average Queue Length in Number of Jobs (Shop)	18.90	17.66
18. Variance of Queue Length in Hours of Work, Average (Machine)	18.51	13.09
19. Variance of Interarrival Times, Average (Machine)	15.89	17.22
20. Variance of Interarrival Times (Shop)	15.82	17.15
21. Variance of Work Arrived Per Period, Average (Machine)	13.09	13.31
22. Variance of Work Arrived Per Period (Shop)	21.13	15.32
23. Variance of Output, Average Machine	18.75	15.12
24. Variance of Output (Shop)	18.51	16.15

Critical Values	
$\alpha = .05$	H = 9.49
$\alpha = .01$	H = 13.28

The rankings can be found in Table 11. An initial observation is that the ranking of the shop utilization was the same, whereas at the low utilization, it appeared more random. Possibly, this could be attributed to the random number generator more so than the dispatching rules since utilization is a measure of the ratio of work load to the capacity, which would imply an ordering of the amount of work.

The work in process measures have some variation from the rankings obtained at low utilization. Most noticeable is that the DSOP and DS rules have moved to the first position for measures 2 and 3. For the remaining measures, SPT and EWIQ retain their predominance. For the due date criteria, only the average tardiness differed significantly from the ranking obtained at low utilization. At higher utilization SPT moves ahead of DSOP and DS which is understandable because there would be less slack time available for each of the jobs. Thus, each job would be in more competition with the others for selection. For the balance indices, the only significant difference is with the Machine Balance Measure which obtained a completely opposite ranking as compared to low utilization. This result is caused by the lack of the dispatching rules to elicit any difference in performance and since the rankings are determined by the observation mean, it would be suspect to give any meaning to this finding. For the network flow criteria there was some

Table 11. Efficiency Order for the Dispatching Rules; 1-DS, 2-DSOP, 3-EWIQ, 4-SPT, 6-FCFS--High Utilization

	No Pool	Math Pool
1. Average Shop Utilization	21643	21643
2. Average Number of Jobs in Shop	43126	43612
3. Average Number of Operations for Jobs in the Shop	21463	24163
4. Average Work (Hours) Done for Jobs in the Shop	21463	24163
5. Average Work in Process (Hours)	43126	43162
6. Time Spent in the System	43126	43612
7. Time Spent in the Shop	43126	43612
8. Average Job Tardiness	42136	43612
9. Variance of Job Tardiness, Average	12643	12643
10. Average Lateness	43126	43612
11. Variance of Lateness, Average	12643	12643
12. Machine Balance Measure	34621	34612
13. Shop Balance Measure	12643	16243
14. Queue Workload Balance	43126	43612
15. Period Queue Balance	41236	46123
16. Variance of Waiting Time Per Operation, Average	61243	61423
17. Average Queue Length in Number of Jobs (Shop)	43126	43612
18. Variance of Queue Length in Hours of Work, Average (Machine)	12634	61243
19. Variance of Interarrival Times, Average (Machine)	26134	34621
20. Variance of Interarrival Times (Shop)	26134	34621
21. Variance of Work Arrived Per Period, Average (Machine)	32614	36421
22. Variance of Work Arrived Per Period (Shop)	12634	21643
23. Variance of Output, Average Machine	42613	46123
24. Variance of Output (Shop)	21634	61243

variation in the rankings with a trend for DSOP and DS to give better performance at high utilization than at low utilization. Measure 18 had the biggest change, with EWIQ moving to fourth from first, and DS and DSOP moving to the top of the list. This could be attributed to the increased congestion in the shop and fluctuation of queue lengths undermining the look ahead feature of EWIQ.

A comparative analysis of the performance measures at the higher utilization was also conducted. This analysis was performed by computing the Spearman rank correlation coefficient for all pairs of measures for the uncontrolled approach and for the mathematical loading approach for the data collected at the high utilization. The correlation coefficient was also computed for the same measure between loading approaches. To ascertain the effect of the high utilization on the capability of the criteria to measure effectiveness, the rank correlation coefficient between the corresponding measures of a loading approach at each level of utilization was computed. In order to calculate this coefficient the data for the DD rule was removed from each set of data at the low utilization. Two levels of significance were used throughout this analysis: for size .001, $r_s = 0.5980$ and for size .01, $r_s = 0.4660$. The results of this analysis are found in Table 12 for the uncontrolled approach and Table 13 for the mathematical pool approach.

Generally, within high utilization, the results of

Table 12. Correlation of Performance Measures--No Pool-High Utilization

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	P	N_L
2				⊕	⊕	⊕	⊕		⊕			-	⊕	⊕	⊖	⊕		⊖	⊖		⊖		⊖	⊕	⊕
3			⊕				⊕	⊕		⊕		+		+			+					⊕		⊕	⊕
4							⊕	⊕		⊕				+								⊕		⊕	⊕
5					⊕	⊕	⊕		⊕				⊕	⊕	-	⊕		⊖	⊖		-		-	⊕	⊕
6						⊕	⊕		⊕			-	⊕	⊕	⊖	⊕		⊖	⊖		⊖		⊖	⊕	⊕
7							⊕		⊕			-	⊕	⊕	⊖	⊕		⊖	⊖		⊖		⊖	⊕	⊕
8									⊕				⊕	⊕		⊕						⊕			⊕
9										⊕		⊕	-		⊕		⊕	+	+		⊕		⊕	⊕	⊕
10												-	⊕	⊕	⊖	⊕		⊖	⊖		⊖		⊖	⊕	⊕
11												⊕	-		⊕		⊕	+	+		⊕		⊕	⊕	⊕
12																								⊕	
13													-		⊕	-	⊕	⊕	⊕		⊕		⊕	⊕	⊕
14														⊕	⊖	⊕		⊖	⊖		⊖		⊖	⊕	⊕
15																⊕						+		⊕	⊕
16																⊖	⊕	+	+		⊕		⊕	⊕	⊕
17																		⊖	⊖		⊖		⊖	⊕	⊕
18																		⊕	⊕		⊕		⊕	⊕	
19																			⊕		⊕		⊕		
20																					⊕		⊕		
21																						-			⊕
22																							⊕	⊕	⊕
23																								⊕	+
24																								⊕	⊕

For + or -
$\alpha = .01$

For ⊕ or ⊖
$\alpha = .001$

P - Math Pool

N_L - No Pool - Low Utilization

Table 13. Correlation of Performance Measures--Math Pool--High Utilization

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	N	P_L
2				⊕	⊕	⊕	⊕	-	⊕	⊖	⊕	-	⊕	+		⊕					⊖	+	-	⊕	⊕
3			⊕					+		⊕	⊖							⊖	⊖	⊖	+			⊕	+
4								+		⊕	⊖							⊖	⊖	⊖	+			⊕	+
5					⊕	⊕	⊕		⊕		+		⊕	⊕		⊕					-	+		⊕	⊕
6						⊕	⊕	⊖	⊕	⊖	⊕	⊖	⊕			⊕		⊕	⊕		⊖		⊖	⊕	⊕
7							⊕	-	⊕	⊖	⊕	-	⊕	+		⊕					⊖		-	⊕	⊕
8								⊖	⊕	⊖	⊕	⊖	⊕			⊕		+	+		⊖		⊖		
9									⊖	⊕	⊖	⊕	-		⊕	-	⊕	⊖	⊖	-	⊕		⊕	⊕	⊕
10										⊖	⊕	⊖	⊕			⊕		⊕	⊕		⊖		⊖	⊕	⊕
11											⊖	⊕	⊖		⊕	⊖	⊕	⊖	⊖	⊖	⊕		⊕	⊕	⊕
12												-	⊕			⊕		⊕	⊕	+	⊖			⊕	-
13													⊖		⊕	-	+	-	-	-	⊕		⊕	⊕	⊕
14														+		⊕		+	+		⊖		-	⊕	⊕
15																+								⊕	⊕
16																	⊕						⊕	⊕	⊕
17																					⊖		-	⊕	⊕
18																		-	-				+	⊕	+
19																			⊕	+	-				
20																				+	-				
21																									
22																							⊕	⊕	⊕
23																								⊕	+
24																								⊕	⊕

For + or -, $\alpha = .01$

For ⊕ or ⊖, $\alpha = .001$

N - No Pool

P_L - Math Pool--Low Utilization

this analysis were the same as for the low utilization. There was a consistent pattern of correlation between the pairs of corresponding measures from the loading approaches similar to that found before. However, from the foregoing discussion, it is obvious that there are some measures that no longer are correlated. There is no longer any correlation between average tardiness, variance of interarrival time to machine and shop, nor between the variance of work arrived per period to a machine. For average tardiness, this corresponds to the change in application of the dispatching rules. The lack of correlation of the variance of the work arrived per period to a machine could be attributed to the inability to distinguish between dispatching rules. But the lack of correlation between the variances of interarrival time must be attributed to the capability of the pool to filter the randomness enabling a more effective control of the shop. For the individual correlations within a loading approach, the first observation is a decrease in the number of correlations between the network flow measures for the pool, which implies that the pool has an effect on the network flow measures. Another observation is that measures 12 and 21 for the uncontrolled have a distinct lack of correlation with the other measures as expected from the Kruskal-Wallis test. Measures 17 and 22 still have good correlations with the other measures, but measure 23 has deteriorated in capability to have the same information content as it did at the lower level.

With respect to the correlations between levels of utilization that will enable a determination of the effect of high utilization, the results are good. That is, there is not much deterioration in the criteria to measure effectiveness. For the mathematical pool, there are high correlations with all measures except 8, 12, 19, 20, and 21. From the previous discussion concerning the pool effect on network parameters, it is not surprising that 19, 20, and 21 did not correlate. Additionally, there was no difference across the dispatching rules for 19 and 20. Measure 8 had little correlation with the other measures at low level, but had a number of correlations at the high level. For the negative correlation computed for measure 12, the author could think of no reason that could be justified to account for the result. For the uncontrolled approach, there were high correlations between all the measures except 12, 18, 19, and 20. The explanation for measure 12 in this loading approach is simply that it did not differentiate between dispatching rules at the high level, whereas there was a significant difference at the low level. The lack of significant association in measure 18 is that the high level had more congestion in the system in general and more fluctuation in the queue length in hours of work because of the heavier workload throughout the system. For the failure of the variances of the interarrival times to correlate, the only plausible reason is that the higher utilization reduces the amount of variation between arrivals, whereas there is more variation at the low level.

5.6 Jackson's Decomposition Principle

Jackson's work in networks of queues has been previously discussed in Chapter II, but for the benefit of the reader, the essential assumptions of the decomposition principle will be reiterated.

(1) Jobs are assigned to machine M on a first come-first served basis.

(2) Arrivals from outside the shop are in a poisson type time series.

(3) A job leaving one machine center goes to another or is finished according to a probability distribution associated with the center it is leaving.

(4) Process times are negative exponentially distributed.

Given that these assumptions hold, the job shop will act like a collection of independent machines that can be analyzed individually.

The first three assumptions were known to hold, but the fourth assumption had to be verified. Thus, the frequency distribution of the interarrival times was collected during the simulation runs for this analysis. For each loading approach using different random number sequences, a machine was picked at random and the frequency distribution analyzed to determine if it was a good fit to the negative exponential distribution. The Chi-squared goodness of fit test was used. The results are in Table 14.

Once the fit of the frequency distribution to the negative exponential distribution was verified for the FCFS rule, it was desired to ascertain the goodness of fit for the other five dispatching rules. Those results are also contained in Table 14.

Of the 18 tests performed to determine the conformity of the frequency distribution to the negative exponential distribution, only five were rejected by the goodness of fit test at size .01, and at size .05 none were rejected. The only consistent pattern for the rejection was with the DD rule and the mathematical pool missed being rejected at size .05 by .47, which could be attributed to the random variation in the model. The rejection of the DD rule could be attributed to the function which assigns the due date since it has already been shown to give results contrary to results reported in the literature. For the results with the other rules, the author conjectures that (except for the DD rule) if the machine centers in a network can be analyzed independently, then the dispatching rule has no effect on the nature of the distribution of the arrivals to a machine. However, the loading approach does have relevance to the parameter of the distribution. As seen in Table 14, the

Table 14. Statistical Results of Jackson's Decomposition Principle. Values of the test statistic in determining if the interarrival times at a machine follow the negative exponential distribution.

	No Pool	Math Pool	Pool Heuristics
Dynamic Slack	38.66	48.45	32.56
Dynamic Slack/Opn	36.72	29.73	45.80
Expected Work in Next Queue	31.89	40.93	34.55
Shortest Processing Time	29.95	43.03	46.61
Due Date	44.80	43.33	48.41
First Come-First Serve	25.58	17.68	32.55
Mean Parameter	.3315	.3023	.3091

Critical Values: $\chi^2_{.05,30} = 43.80$

$\chi^2_{.01,30} = 50.90$

parameter computed from the data for the two pool approaches are lower than that for the uncontrolled arrival process, which adds credence to the conjecture that the pool loading approaches filter out part of the randomness.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The purpose of this research has been to investigate the differences in discrete network flow patterns under various dispatching methodologies and to identify relevant measures of network flow. This has been accomplished by determining which of the network flow measures defined contain the same information as previously used measures. From the comparative analysis it is now known that network flow measures contain as much information as previously used performance criteria. The two best network flow measures identified in this research are average queue length in number of jobs for the shop and the average machine variance of the output. These two are called the best because they had consistently high positive correlation. However, the following network flow measures also had high correlation although the association was mixed between positive and negative; variance of interarrival times, average for a machine; variance of interarrival times to the shop; variance of work arrived per period to the shop; and variance of output from the shop. All of these measures could be used to reduce the variability of work flow in the network.

Additionally, several other conclusions are possible from this research. This experiment has indicated which dispatching rules provide the best results for a given performance criterion, a class of criteria or a logical set of criteria. This ranking of the tested dispatching rules not only has the ordinal ranking, but also the win-loss percentage which gives a degree of preference of one rule over another.

From studying the arrival process as varied by the loading approach, it has been shown that the ordering of the dispatching rules is independent of the loading approach. Although not addressed in this research, the job pool concept will give better results for a performance measure than without a pool. For details see [26]. The job pool concept is an effective variance reduction technique, but does not reduce the variance enough to change the nature of the arrival process, although it does change the parameter of the distribution.

In this research it was shown that the Jackson decomposition principle also applied to DS, DSOP, EWIQ, and SPT, which implies that once a system is verified to have independent machine centers, then the dispatching rule has no effect on the nature of the interarrival distribution to a given machine. The results for the DD rule kept it from being included in these remarks. It is not known whether the results for DD are attributable to the nature of the rule or the nature of the function used to assign due dates.

The effect of high utilization on the information content of the performance criteria is that generally there is no difference. There were some measures that responded adversely, but in general, this was not the case. The mathematical pool had the most detrimental effect on the network flow measures, but there were still measures that correlated with previously used criteria. The average queue length in number of jobs for the shop remained as the best network measure.

6.2 Recommendations

There are other areas of research that could be undertaken as extensions of this research with profitable results. Since the network flow measures are known to be as good as other criteria in evaluating a schedule, other good network flow measures need to be identified. This research focused on "variance" type criteria whereas the mean value might have been as good or better.

Jackson's decomposition principle has revealed that this model could be analyzed analytically as ten separate machines. Possibly as an extension of this research, one of the machines could be randomly selected and the model used again to generate the job patterns through the shop for analysis in the one machine setting. The results could then be used to make inferences or generalizations pertaining to the ten machine shop. A complicating factor is the reduction of the parameter of the arrival distribution.

A study similar to this one could be performed as a research topic using fewer performance criteria (selected from the grouping in this research) and more dispatching rules (from Appendix B) to provide more insight into the relative power of the rules. Additionally, coupling the job pool with the mathematical loading algorithm with Deane's flow controlled methodology could be included to determine the effectiveness of the combined approaches. Research of this nature could possibly result in dispatching rules that produce better performance than attained to date.

A good loading algorithm for the job pool would be a parallel server queueing system with as many servers as the shop has machines. The algorithm would necessarily have to operate stochastically with state change feedback from the job shop. In this case, the variance of the arrival process would be reduced sufficiently to disturb the nature of the distribution, which could be verified by Jackson's decomposition principle. Research to find such a loading algorithm coupled with the job pool that could perform this well, would open an entire new realm of study for the job shop.

APPENDICES

APPENDIX A

The notion used in defining these measures is:

a	number of operations
h	number of hours in a scheduling period
n	number of jobs in the simulation
p	number of scheduling periods
i	subscript for machines
j	subscript for periods
k	subscript for jobs
l	subscript for operations
a(t)	number of operations done at time t
A_k	time allowance for job k
b_i	interarrival time for machine i
b'	interarrival time to machine i for shop
C_k	completion time for job k
D_k	due date for job k
e_{ij}	output for machine i in period j
E_i	efflux or output per period for machine i
F_k	time spent in the system
F_k'	time spent in the shop for job k
L_k	lateness for job k
M_i	machine balance measure index for machine i
N(t)	number of jobs in the shop at time t

$P_{i,k}$ processing time on machine i for job k

PQ_j period queue balance index for period j

Q_i queue workload balance index for machine i

R_k release time for job k to the system which includes the pool, if used

R_k' release time for job k to the shop

τ_k tardiness for job k

σ^2 the form of the equation is the reason for this notation. There is no statistical meaning implied.

w_{ij} work done by machine i in period j

w_{ij}' work awaiting processing in hours for machine i in period j

w(t) work done in hours for jobs in the shop at time t

w'(t) work awaiting processing in hours at time t

$W_{i,k}$ waiting time in queue i for job k (i=o is for the job pool)

The performance measures are:

1. Average shop utilization--This is the ratio of the total work load to the shop machine capacity for a given period.

$$\overline{w} = \frac{1}{pm} \sum_{j=1}^{p} \sum_{i=1}^{m} w_{ij}$$

$$u = \frac{\overline{w}}{h} \cdot 100$$

2. Average number of jobs in the shop--This is the ratio of the sum of the number of jobs for each instant of

time to the total time of the simulation.

$$\overline{N}(t) = \frac{1}{t}\int_{o}^{t} N(t)dt$$

3. Average number of operations performed per job in the shop--This is the ratio of the sum of the number of operations performed for each instant of time to the total time of the simulation.

$$\overline{a}(t) = \frac{1}{t}\int_{o}^{t} a(t)dt$$

4. Average work done in hours for jobs in the shop--This is the ratio of the sum of the work done in hours for each instant of time to the total time of the simulation.

$$\overline{w}(t) = \frac{1}{t}\int_{o}^{t} w(t)dt$$

5. Average work in process in hours--This is the ratio of the sum of the work awaiting processing in hours for each instant of time to the total time of the simulation. A job is in process at any time between the beginning and the end of its processing.

$$\overline{w}'(t) = \frac{1}{t}\int_{o}^{t} w'(t)dt$$

6. Average time spent in the system for job k--This can be defined in two ways: (a) The ratio of the sum over all machines and all jobs of processing time at the requisite machines and the waiting time in each machine queue prior to processing to the total number of jobs. If a job pool is used, the time spent waiting prior to entry into the shop must be included, i.e. when i=o, the job is in the pool awaiting entry into the shop; (b) The ratio of the sum over all jobs of the difference between completion time and system release time to the total number of jobs

a. $$\overline{F}_k = \frac{1}{n} \sum_{i=o}^{m} \sum_{k=1}^{n} (P_{i,k} + W_{i,k})$$

b. $$\overline{F}_k = \frac{1}{n} \sum_{k=1}^{n} (C_k - R_k)$$

7. Average time spent in the shop for job k. This can be defined in two ways: (a) The ratio of the sum over all machines and all jobs, of processing time at the requisite machines and the waiting time in each machine queue prior to processing to the total number of jobs; (b) The ratio of the sum over all jobs of the difference between completion time and shop release time to the total number of jobs.

a. $$F'_k = \frac{1}{n} \sum_{i=1}^{m} \sum_{k=1}^{n} (P_{i,k} + W_{i,k})$$

b. $$\overline{F}'_k = \frac{1}{n} \sum_{i=1}^{n} (C_k - R'_k)$$

8. Average job lateness--This is the ratio of difference between completion time and the due date of a job, or the difference between job flow time and job allowance time to the total number of jobs.

$$L_k = C_k - D_k = F_k - A_k$$

$$\text{(a)} \quad \overline{L} = \frac{1}{n} \sum_{k=1}^{n} (C_k - D_k)$$

$$\text{(b)} \quad \overline{L} = \frac{1}{n} \sum_{k=1}^{n} (F_k - A_k)$$

9. Variance of the lateness distribution--This is the ratio of the sum over all jobs of the square of the difference between each job lateness and average job lateness to the total number of jobs less one.

$$\sigma_L{}^2 = \frac{1}{n-1} \sum_{k=1}^{n} (L_k - \overline{L})^2$$

10. Average job tardiness--This is the ratio of the maximum of 0 or the job lateness to the total number of jobs.

$$\tau_k = \max\ (0,\ L_k)$$

$$\tau = \frac{1}{n} \sum_{k=1}^{n} \tau_k$$

11. Variance of the tardiness distribution--This is the ratio of the sum over all jobs of the square of the difference between each job tardiness and average job tardiness to the total number of jobs less one.

$$\sigma_T^2 = \frac{1}{n-1} \sum_{k=1}^{n} (\tau_k - \overline{\tau})^2$$

12. Machine Balance Measure--This is the "variance" in the work done by each machine over all time periods. Then an overall index is obtained by averaging overall machines.

$$M_i = \frac{1}{p} \sum_{j=1}^{p} (w_{ij} - \overline{w}_i)^2$$

$$MWB = \frac{1}{m} \sum_{i=1}^{m} M_i$$

13. Shop Balance Measure--This is the "variance" of the work done in the shop as a whole taken over time.

$$SWB = \frac{1}{p} \sum_{j=1}^{p} \left(\sum_{i=1}^{m} w_{ij} - \sum_{i=1}^{m} \overline{w}_i \right)^2$$

$$= \frac{1}{p} \sum_{j=1}^{p} (m\overline{w}j - \overline{w})^2$$

14. Queue Workload Balance--This is the "variance" of the queue size in number of jobs for each machine taken over time. An overall index is then obtained by averaging over all machines.

$$Q_i = \frac{1}{p} \sum_{j=1}^{p} (l_{ij} - \bar{l}_i)^2$$

$$QWB = \frac{1}{m} \sum_{i=1}^{m} Q_i$$

15. Period Queue Balance--This is the "variance" of queue size over all machines for each time period. An overall index is then obtained by averaging over all time periods.

$$PQ_j = \frac{1}{m} \sum_{i=1}^{m} (l_{ij} - \bar{l}_i)^2$$

$$PQWB = \frac{1}{p} \sum_{j=1}^{p} PQ_j$$

APPENDIX B

A LIST OF COMMONLY USED DISPATCHING RULES FROM [42]

1. Random selection for service

* 2. First-come, first-served

3. First-in-system, first-served

4. Last-come, first-served

* 5. Shortest imminent operation (may include set-up considerations)

6. Static slack: due date minus the time of arrival at the machine center

7. Static slack per remaining number of operations

* 8. Due date

* 9. Dynamic slack: due date minus the remaining expected flow time minus the current date

10. Dynamic slack/remaining processing time

*11. Dynamic slack/remaining number of operations

12. Two class shortest operation: select first-come, first-served within each of two classes defined by operation length

13. Truncated shortest operation: jobs which have waited more than k units of time take precedence

14. Alternate shortest operation, first-come, first-served

*15. Subsequent operation (look ahead): select job which will go to a queue with less than k time units of work waiting. Use shortest operation among jobs for the critical queue.

16. Two class truncated shortest operation: take shortest operation within critical class based on negative dynamic slack; if critical class is empty, take shortest operation

17. Cost/time: pick critical job (negative dynamic slack) by shortest operation; for late, but not critically late, pick largest cost of lateness/operation time; for early jobs, use shortest operation

18. Dynamic slack among all imminent jobs: the dynamic slack rule is applied to all jobs in the queue and also to those jobs that are in process and will join the queue after their current operation is complete

19. Fewest remaining operations

20. Longest imminent operation

21. Least work remaining

22. Most work remaining

23. Greatest total work for all centers on the routing

*Dispatching rules used in the research.

APPENDIX C

USER PROGRAMS FOR THIS SIMULATION MODEL

A description of the user programs written for this simulation of the job shop.

(1) Subroutine ARIVL: This subroutine is called when a new arrival time is reached. The subroutine then generates the job attributes, number of operations, the machine number and processing time for the first operation, the remaining sequence of machines and their respective processing times, and with the information known, finally a due date. The job is then given a file location and placed in it. The next arrival time is then generated and the time is placed in the GASP file as the next arrival event.

(2) Subroutine CLEAR: This subroutine reinitializes all statistical arrays after a prescribed run-in period without disturbing its shop status.

(3) Subroutine COLL: This subroutine is used at the end of every scheduling period. Primarily, it calculates and updates the statistics kept on a scheduling period basis. When a job pool is used, this subroutine will call the matrix generator subprogram. Additionally, the routine acts on end of run in period and end of simulation conditions.

(4) Subroutine DYNAM: This subroutine is utilized

in conjunction with the dynamic dispatching rules, dynamic slack, and dynamic slack per remaining operations. Each time a job is to be selected from a machine queue, subroutine DYNAM is called to compute the priorities.

(5) Subroutine ENDSV: This subroutine is called when an end of service has been reached for a machine. Statistics are then taken for the job depending on its completion posture. If all of the processing for the job has been completed, terminal job statistics are collected and the job is removed from the system. On the other hand, if there are remaining operations to be done, the job attributes are updated and subroutines are called to move the job in its next queue. After these actions are completed the subroutine then checks the queue to determine which job to bring in for processing. This action depends on the dispatching rule being used. If the queue has one or more jobs, statistics on job waiting times and shop workload are calculated. When the queue is empty, machine utilization is updated.

(6) Subrouting ENSIM: This subroutine is called at the end of the simulation to calculate and print the results. There is also an option to begin another simulation run with a different dispatching rule. When the option is envoked, ENSIM must reinitialize the non-GASP variable and call GASP to start the new run.

(7) Subroutine EVNTS: This subroutine directs GASP

to the proper subroutine to handle the transactions associated with starting the simulation, an arrival to the shop, an end of service, or to collect statistics at the end of a schedule period.

(8) Subroutine EWIQ: This subroutine is used in conjunction with the expected work in next queue dispatching rule. The routine indicates the job in queue which will proceed to the machine with the least expected work in queue.

(9) Subroutine GENMAT: This subroutine generates the matrix required by the loading algorithm to select those jobs to be moved from the pool to the shop. The matrix generation is accomplished by using job attributes from the job file. When the pool is not being used, this routine is not active. However, when it is used, it calls the loading algorithm which has been selected, either the loading heuristics or the mathematical program.

(10) Subroutine JOBDEC: This subroutine uses the answer from LPI to decide which jobs to load from the pool into the shop, specifically the appropriate machine queue.

(11) Subroutine LPI: This routine is essentially a linear programming code extended to include a bounded variable feature. JOBDEC is called from this routine.

(12) MAIN PROGRAM: This is the program that gets the simulation started. In MAIN, the value of the parameters are read, the non-GASP variables are initialized, and the executive subroutine, GASP, is called to take over control of

the simulation.

(13) Subroutine POOLHE: This is the loading heuristic subroutine that uses "rules of thumb" to select jobs from the pool to load into the shop.

(14) Subroutine PTJOB: This subroutine places the jobs in their destination position, either job pool, machine queue, or on the machine. Which action is taken is dependent on whether the job is a new arrival, if a pool is being used, and on the status of the machine. Interarrival times to the pool and each machine are collected. If a job is put on a machine, the workload in the machine status is changed. If the machine was idle, the time of the completion event is set.

(15) Subroutine START: This subroutine generates arrivals to preload the shop and pool if one is being used. New arrivals continue to be generated until the shop and pool have reached their proper number of jobs. Then the clock is set to zero to begin the simulation.

APPENDIX D

FORTRAN LISTING OF SUBROUTINES CHANGED FOR THIS RESEARCH

The following list contains the variable parameter conditions as set for this research:

(1) NM--number of machines, 10

(2) NTOTPD--number of periods the simulation is to run, 500

(3) NRSET--number of runs in periods for the simulation, 50

(4) PLEN--length of one scheduling period in hours, 8

(5) ISEED--random number seed to use

Run 1-329963 Run 2-411719 Run 3-392819

Run 4-349387 Run 5-900131

(6) ITYPE--not used

(7) N RULE--dispatching rule to use

1. Dynamic Slack
2. Dynamic Slack per Operation
3. Expected Work in Next Queue
4. Shortest Processing Time
5. Due-Date
6. First Come-First Served

(8) IDUE--method of job due date generation, 1

(9) NLDR--loading approach to use

0 no pool
1 mathematical pool
5 pool heuristics

(10) ARATE--arrival rate

Low utilization .5300
High utilization .6000

(11) NARR--type of arrivals, 1

(12) FACDUD--weights for the due dates, 80

(13) SINPER--number of periods in sine curve, 16

(14) NPREL--number of jobs to preload in shop, 45

(15) NPREP--number of jobs to preload in pool, 25

(16) NDESL--switch to determine calculation of aggregate desired load, 1

(17) DESLF--factor for calculation of desired management load for math pool

Low utilization --4.25
High utilization --6.00

(18) NDML--switch to calculate queue load, 1

(19) DMLF--factor for queue load calculation, .40

(20) TIMEF--factor to extend the time generated for a machine operation, 1

(21) CAPM--machine capacity, machine j,8

The subroutines that were changed for this research follow.

```
BELLER-RICHA*SHOPQUEUE.COLL
      SUBROUTINE COLL(NSET)
C
C     ***  EVENT SUBROUTINE TO COLLECT STATISTICS AT
C     ***  THE END OF EVERY SCHEDULING PERIOD AND TO
C     ***  CALL THE LOADING ROUTINE
C
      DIMENSION NSET(35,1),SOPLD2(10),QLOAD2(10),XAVL(35)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,
     2ISEED,TNOW,TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(25),
     3KOF,KLE,KOL,ATRIB(33),ENQ(25),INN(25),JCELS(20,32),
     4KRANK(25),JCLR,MAXNQ(25),MFE(25),MLC(25),MLE(25),
     5 NCELS(20),NQ(25),PARAM(40,4),QTIME(25),SSUMA(35,5)
     6,SUMA(130,5),NAME(6),NPROJ,MON,NDAY,NYR
     1,ARS(35)
      COMMON PLEN,NTPDS,NTOTPD,NM,XISYS,XWKSY,IDUE,
     1ITYPE,MNEXT,NEN,NLV,NHELD,WB(10),WBM(10),X(10,10),
     2          BUS(10),NRSET,NRULE,MNOW,NRST,NENDS,NHOL,NRL,
     3WWW(10),SEED,ARATE,LOC(200),MAX,AR(11)
      COMMON NPREL,NPREP,NDESL,MDML,CAPM(10),DESL(10),
     1DQL(10),DESLF,DMLF,QLOAD(10),XOPS,XWKS,TIMEF(10),
     2NSTSW,NLDR,NARR,SHOPLD(10)
      COMMON A(25,200),KBV(15),C(200),FACDUD
      COMMON ICOUNT,NCOUNT,SINPER,MSW(10),AVGLD9
C
C     ***  SCHEDULE THE NEXT DATA COLLECTION POINT
C
      ATRIB(2)=3.0
      ATRIB(1)=TNOW+PLEN
      CALL FILEM (1,NSET)
      NTPDS=NTPDS+1
      ISCALE=SCALE+.000001
      NTP=NTPDS-1
      TS=0.0
      TOT=0.0
C*****
C***** COLLECT DATA ON THE WORK ARRIVED PER PERIOD TO A MACHINE
C***** COLLECT DATA ON THE WORK ARRIVED PER PERIOD TO THE SHOP
C*****
      DO 11 I = 1 , NM
      I83=I+82
      DAR=ARS(I)
      CALL COLCT (DAR,I83,NSET)
      I94= 93+I
      I22=I+21
      CALL COLCT(ARS(I22),I94,NSET)
      ARS(I22)=0.0
   11 ARS(I)=0.0
      DAR =ARS(11)
      CALL COLCT(DAR,93,NSET)
      ARS(11) = 0.0
      CALL COLCT (ARS(32),104,NSET)
      ARS(32) = 0.0
C
C     ***  UPDATE TIME INTEGRATED STATISTICS ON MACHINES
C     ***  AND COMPUTE STATISTICS ON FACILITY UTILIZATION
```

```
C      ***  DURIN THE PERIOD
C
       AP=0.0
       BP=0.0
       DO 10 I=1,NM
       CALL TMST (BUS(I),TNOW,I,NSET)
       UT=SSUMA(I,3)/PLEN*100.0
       WB(I)=WB(I)/PLEN*100.0
       TS=TS+SSUMA(I,3)
       WBM(I)=WBM(I)+SSUMA(I,3)*SSUMA(I,3)
       TOT=TOT+WB(I)
       WWW(I)=WWW(I)+WB(I)
       CALL COLCT (UT,I,NSET)
       AP=AP+SSUMA(I,3)
       BP=BP+SSUMA(I,3)*SSUMA(I,3)
       WB(I)=0.0
    10 SSUMA(I,3)=0.0
       AP=AP/FLOAT(NM)
       BP=BP/FLOAT(NM)
       BP=BP-AP**2
       CALL COLCT(BP,70,NSET)
       CP=0
       DP=0
       NM1=NM+1
       DO 12 I=2,NM1
       I1=I-1
       XNQ=NQ(I)
       XC=(ENQ(I)+XNQ*(TNOW-QTIME(I)))
       IF (TNOW.LE.0.001) XAVL(I1)=0.0
       AVQ=(XC-XAVL(I1))/PLEN
       CP=CP+AVQ
       DP=DP+AVQ**2
    12 XAVL(I1)=XC
       CP=CP/FLOAT(NM)
       DP=DP/FLOAT(NM)
       DP=DP-CP**2
       CALL COLCT(DP,71,NSET)
       ATS=TS/FLOAT(NM)
       ATOT=TOT/FLOAT(NM)
       CALL COLCT (ATS,14,NSET)
       CALL HISTO (ATS,0.5,0.5,3,NSET)
       AT=ATOT
       CALL HISTO (AT,6.0,6.0,4,NSET)
C
C      ***  CHECK IF A JOB POOL IS BEING USED
C
C
       R66=NQ(12)
       CALL COLCT (R66,66,NSET)
       IF (NLDR.EQ.0) GO TO 39
C
C      ***  POOL IS BEING USED. CALL SUBROUTINES TO LOAD THE
C      ***  SHOP
C
       IF (NQ(12).EQ.0) GO TO 39
       CALL GENMAT (NSET)
C
```

```
C     ***  ADJUST AGGREGATE SHOP LOAD FOR EACH MACHINE AND
C     ***  QUEUE LOAD FOR PARTIALLY COMPLETED JOBS
C
   39 R67=NQ(12)
      CALL COLCT (R67,67,NSET)
      IF (MSW(4).EQ.0) GO TO 40
      IF (NQ(12).LT.1) GO TO 40
      J=0
      N1=MFE(12)
   15 J=J+1
      NFIRST=FLOAT(NSET(11,N1))/SCALE+.0001
      IF (BUS(NFIRST)) 25,25,20
   20 N1=NSET(MX,N1)
      IF (N1.NE.7777) GO TO 15
      GO TO 40
   25 N2=NSET(MX,N1)
      CALL RMOVE(N1,12,NSET)
      CALL COLCT(1.0,69,NSET)
      MNEXT=ATRIB(11)+0.0001
      CALL PTJOB(3,NSET)
      N1=N2
      IF (N1.NE.7777) GO TO 15
   40 N1=MFE(1)
   45 IF (FLOAT(NSET(2,N1))/SCALE.GT.1.0) GO TO 60
      TILEFT=(NSET(1,N1))/SCALE-TNOW
      M1=FLOAT(NSET(11,N1))/SCALE+.000001
      SOPLD2(M1)=SHOPLD(M1)+ (TILEFT*CAPM(M1))/8.0
      QLOAD2(M1)= QLOAD(M1)+ (TILEFT*CAPM(M1))/8.0
   60 N1=NSET(MX,N1)
      IF (N1.NE.7777) GO TO 45
C
C     ***  CALCULATE DEVIATIONS FROM BALANCE
C
      DBALT=0.0
      DO 70 J=1,NM
      DBAL   =DESL(J)-SOPLD2(J)
      N30=J+30
      D30=DBAL
      CALL COLCT (D30,N30,NSET)
      D30AB=ABS(D30)
   70 DBALT=DBALT+D30AB
      CALL COLCT (DBALT,41,NSET)
C
C     ***  CALCULATE ADDITIONAL DEVIATIONS FROM BALANCE,IF
C     ***  REQUIRED,DEPENDING ON LOADING RULE USED.
C
      DBALQT=0.0
      DO 75 J=1,NM
      DBALQ   =DQL(J)-QLOAD2(J)
      N53=J+53
      D53=DBALQ
      CALL COLCT (D53,N53,NSET)
      D53AB=ABS(D53)
   75 DBALQT=DBALQT+D53AB
      CALL COLCT (DBALQT,64,NSET)
   80 IF (NTPDS.GE.NRST) CALL CLEAR (NSET)
      IF (NTPDS.LT.NTOTPD) RETURN
```

```
      CALL ENSIM (NSET)
      RETURN
      END
@PRT SHOPQUEUE.ENDSV
```

```
BELLER-RICHA*SHOPQUEUE.ENDSV
            SUBROUTINE ENDSV (NSET)
      C
      C     ***  EVENT SUBROUTINE CALLED WHEN AN END OF SERVICE
      C     ***  HAS OCCURRED FOR A JOB OPERATION
      C
            DIMENSION NSET(35,1)
            COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
           1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,
           2ISEED,TNOW,TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(25),
           3KOF,KLE,KOL,ATRIB(33),ENQ(25),INN(25),JCELS(20,32),
           4KRANK(25),JCLR,MAXNQ(25),MFE(25),MLC(25),MLE(25),
           5 NCELS(20),NQ(25),PARAM(40,4),QTIME(25),SSUMA(35,5)
           6,SUMA(130,5),NAME(6),NPROJ,MON,NDAY,NYR
           1,ARS(35)
            COMMON PLEN,NTPDS,NTOTPD,NM,XISYS,XWKSY,IDUE,
           1ITYPE,MNEXT,NEN,NLV,NHELD,WB(10),WBM(10),X(10,10),
           2        BUS(10),NRSET,NRULE,MNOW,NRST,NENDS,NHOL,NRL,
           3WWW(10),SEED,ARATE,LOC(200),MAX,AR(11)
            COMMON NPREL,NPREP,NDESL,NDML,CAPM(10),DESL(10),
           1DQL(10),DESLF,DMLF,QLOAD(10),XOPS,XWKS,TIMEF(10),
           2NSTSW,NLDR,NARR,SHOPLD(10)
            COMMON A(25,200),KBV(15),C(200),FACDUD
            COMMON ICOUNT,NCOUNT,SINPER,MSW(10),AVGLD9
            MNOW=ATRIB(11)+0.00001
            MNEXT=ATRIB(13)+0.00001
            CALL TMST (XOPS,TNOW,13,NSET)
            XOPS=XOPS+1.0
            CALL TMST (XWKS,TNOW,14,NSET)
            XWKS=XWKS+ATRIB(12)
            ATRIB(32)=ATRIB(32)+ATRIB(12)
            ATRIB(5)=ATRIB(5)-1.0
      C*****
      C***** COLLECT DATA ON THE OUTPUT OF A MACHINE
      C***** COLLECT DATA ON THE OUTPUT  FROM THE SHOP
      C*****
            I22 = 21 + MNOW
            ARS(I22) = ARS(I22) + 1
            ARS(32) = ARS(32) + 1
            IF (ATRIB(5)) 10,10,60
      C
      C     ***  COLLECT STATISTICS ON THE JOB LEAVING THE SYSTEM
      C
         10 TISYS=TNOW-ATRIB(3)
            CALL COLCT (TISYS,11,NSET)
            NOP=ATRIB(10)+0.00001
            NP23=NOP+22
            CALL COLCT (TISYS,NP23,NSET)
            CALL TMST (XISYS,TNOW,12,NSET)
            XISYS=XISYS-1.0
            CALL TMST (XWKSY,TNOW,11,NSET)
            XWKSY=XWKSY-ATRIB(9)
            DDD=ABS(TNOW-ATRIB(4))
            CALL COLCT (DDD,15,NSET)
            TLATE=TNOW-ATRIB(4)
            CALL COLCT (TLATE,12,NSET)
            CALL HISTO (TLATE,-10.0,2.0,1,NSET)
```

```
          TARDY=TLATE
          IF (TLATE.LT.0.0) TARDY=0.0
          CALL COLCT (TARDY,13,NSET)
          TSYNPL=TNOW-ATRIB(33)
          CALL COLCT (TSYNPL,42,NSET)
          NP40=NOP+39
          CALL COLCT (TSYNPL,NP40,NSET)
          TIPOOL=ATRIB(33)-ATRIB(3)
          CALL COLCT (TIPOOL,48,NSET)
          PERPOL=TIPOOL/PLEN+0.5
          NPEPOL=PERPOL
          CALL HISTO (NPEPOL,1.0,1.0,16,NSET)
          NP46=NOP+45
          CALL COLCT (TIPOOL,NP46,NSET)
          B=FLOAT(NTPOS-1)*PLEN
          BDUE=ATRIB(4)
          IF (BDUE.LT.B) GO TO 30
          IF (BDUE.LT.TNOW) GO TO 20
          LP= (TNOW-BDUE/PLEN)-.9999999
          GO TO 40
       20 LP=0
          GO TO 40
       30 LP=(B-BDUE)/PLEN+.999999
       40 XP=LP
          CALL HISTO (XP,-10.5,1.0,2,NSET)
          XOPS=XOPS-ATRIB(10)
          XWKS=XWKS-ATRIB(9)
          NLV=NLV+1
          JOB=ATRIB(30)+.001
          LOC(JOB)=0
          IF (JOB.NE.MAX) GO TO 80
       50 MAX=MAX-1
          JOB=JOB-1
          IF (LOC(JOB).LE.0) GO TO 50
          GO TO 80
C
C         *** THE JOB IS NOT LEAVING THE SYSTEM
C         *** UPDATE THE JOB ATTRIBUTES
C
       60 IF (NRULE.LE.3) ATRIB(6)=ATRIB(6)-ATRIB(12)
          LRM=ATRIB(5)+.001
          LR=2*LRM+9
          DO 70 I=11,LR,2
          ATRIB(I)=ATRIB(I+2)
       70 ATRIB(I+1)=ATRIB(I+3)
          ATRIB(LR+2)=0.0
          ATRIB(LR+3)=0.0
          CALL PTJOB (2,NSET)
C
C         ***  CHECK MACHINE QUEUE FOR ANY JOBS
C         ***  AVAIABLE FOR PROCESSING
C
       80 IF (NQ(MNOW+1)) 90,90,100
C
C         ***  THERE ARE NO JOBS IN THE QUEUE
C
       90 CALL TMST (BUS(MNOW),TNOW,MNOW,NSET)
```

```
      BUS(MNOW)=0.0
      IF (MSW(2).EQ.0) GO TO 93
      IF (NLDR.EQ.0) GO TO 93
      CALL COLCT(1.0,68,NSET)
      IF (NQ(12).LT.1) GO TO 93
      IF (MSW(3).EQ.0) GO TO 88
      IF (SSUMA(MNOW,3).GE.AVGL09) GO TO 93
C
C     ***  TRY TO MOVE JOB FROM POOL TO EMPTY MACHINE
C
   88 J=0
      N1=MFE(12)
   91 J=J+1
      NFIRST=FLOAT(NSET(11,N1))/SCALE+.0001
      IF (NFIRST.EQ.MNOW) GO TO 92
      N1=NSET(MX,N1)
      IF (N1.NE.7777) GO TO 91
C
C     ***  NO JOB WAS FOUND THAT COULD HELP IDLE MACHINE
C
      GO TO 93
C
C     ***  PUT JOB FROM POOL IN IDLE MACHINE
C
   92 CALL RMOVE(N1,12,NSET)
      CALL COLCT (1.0,69,NSET)
      MNEXT=ATRIB(11)+.00001
      CALL PTJOB(3,NSET)
   93 RETURN
C
C     ***  MORE THAN ONE JOB IS AVAIABLE. COMPUTE
C     ***  PRIORITIES AND BRING IN THE JOB WITH THE
C     ***  HIGHEST PRIORITY FROM THE QUEUE.
C
  100 MN1=MNOW+1
      IF (NQ(MN1).EQ.1) GO TO 120
      IF (NRULE.EQ.0.OR.NRULE.GT.3) GO TO 120
      IF (NRULE.GT.2) GO TO 110
      CALL DYNAM (MBEST,NSET)
      CALL RMOVE (MBEST,MN1,NSET)
      GO TO 130
  110 CALL WKINQ (MBEST,NSET)
      IF (MBEST.EQ.0) GO TO 120
      CALL RMOVE (MBEST,MN1,NSET)
      GO TO 130
  120 CALL RMOVE (MFE(MN1),MN1,NSET)
C
C     ***  COMPUTE THE WAITING TIME FOR THE JOB AND
C     ***  DECREASE THE WORKLOAD IN THE MACHINE QUEUE.
C
  130 WT=TNOW-ATRIB(8)
      MN15=MNOW+15
      CALL COLCT (WT,MN15,NSET)
C*****
C***** COLLECT THE THE DATA ON THE QUEUE LENGTH IN HOURS OF WORK ****
C***** COLLECT DATA ON THE QUEUE LENGTH IN HOURS OF WORK TO THE SHOP
C*****
```

```
      M15 = 14+MNOW
      M12 = 11+MNOW
      XXX=ARS(M12)
      CALL TMST(XXX,TNOW,M15,NSET)
      ARS(M12)=ARS(M12)-ATRIB(12)
      QLOAD(MNOW)=QLOAD(MNOW)-ATRIB(12)
      SHOPLD(MNOW)=SHOPLD(MNOW)-ATRIB(12)
      TIMEVT=ATRIB(12) *(8.0/CAPM(MNOW ))
      ATRIB(1)=TNOW+TIMEVT
      ATRIB(2)=1.0
      JOB=ATRIB(30)+.001
      LOC(JOB)=MFA
      CALL FILEM(1,NSET)
      RETURN
      END
@PRT SHOPQUEUE.ENSIM
```

```
BELLER-RICHA*SHOPQUEUE.ENSIM
      SUBROUTINE ENSIM (NSET)
C
C     ***  SUBROUTINE USED TO PRINT SIMULATION RESULTS
C
      DIMENSION NSET(35,1)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,
     2ISEED,TNOW,TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(25),
     3KOF,KLE,KOL,ATRIB(33),ENQ(25),INN(25),JCELS(20,32),
     4KRANK(25),JCLR,MAXNQ(25),MFE(25),MLC(25),MLE(25),
     5 NCELS(20),NQ(25),PARAM(40,4),QTIME(25),SSUMA(35,5)
     6,SUMA(130,5),NAME(6),NPROJ,MON,NDAY,NYR
     1,ARS(35)
      COMMON PLEN,NTPDS,NTOTPD,NM,XISYS,XWKSY,IDUE,
     1ITYPE,MNEXT,NEN,NLV,NHELD,WB(10),WBM(10),X(10,10),
     2        BUS(10),NRSET,NRULE,MNOW,NRST,NENDS,NHOL,NRL,
     3WWW(10),SEED,ARATE,LOC(200),MAX,AR(11)
      COMMON NPREL,NPREP,NDESL,NDML,CAPM(10),DESL(10),
     1DQL(10),DESLF,DMLF,QLOAD(10),XOPS,XWKS,TIMEF(10),
     2NSTSW,NLDR,NARR,SHOPLD(10)
      COMMON A(25,200),KBV(15),C(200),FACDUD
      COMMON ICOUNT,NCOUNT,SINPER,MSW(10),AVGLD9
      PRINT 160,NLDR,NRULE
      CALL TMST (XWKSY,TNOW,11,NSET)
      CALL TMST (XISYS,TNOW,12,NSET)
      CALL TMST (XOPS,TNOW,13,NSET)
      CALL TMST (XWKS,TNOW,14,NSET)
      DO 10 I=1,NM
   10 CALL TMST (BUS(I),TNOW,I,NSET)
      NTPDS=NTPDS-NRSET
      NNTP=NTOTPD-NRSET
      WRITE (6,170) NM,NRSET,NNTP,PLEN
      WRITE (6,171) (MSW(J),J=1,10)
      IF(MSW(5).GT.0) GO TO 13
      WRITE (6,172)
      XN=NTPDS
      DO 12 I=1,NM
      J30=30+I
      XM1=SUMA(J30,1)/FLOAT(NTPDS)
      J53=53+I
      XM2=SUMA(J53,1)/FLOAT(NTPDS)
   12 WRITE (6,173) I,XM1,XM2
   13 CONTINUE
      XM3=SUMA(41,1)
      XM4=SUMA(64,1)
      XN3=SUMA(41,3)
      XN4=SUMA(64,3)
      XS3=SUMA(41,2)
      XS4=SUMA(64,2)
      AVG3=XM3/XN3
      AVG4=XM4/XN4
      VAR3=(((XN3*XS3)-(XM3*XM3))/(XN3*(XN3-1.0)))
      VAR4=(((XN4*XS4)-(XM4*XM4))/(XN4*(XN4-1-0)))
      WRITE (6,174)
      WRITE (6,175) AVG3,VAR3
      WRITE (6,176)
```

```
      WRITE (6,175) AVG4,VAR4
      J=11
      DO 16 I=1,3
      XM5=SUMA(J,1)
      XS5=SUMA(J,2)
      XN5=SUMA(J,3)
      AVG5=XM5/XN5
      VAR5=(((XN5*XS5)-(XM5*XM5))/(XN5*(XN5-1.0)))
      IF (I.GT.1) GO TO 14
      WRITE (6,177)
      J=48
      GO TO 16
   14 IF (I.GT.2) GO TO 15
      WRITE (6,178)
      J=42
      GO TO 16
   15 WRITE (6,179)
   16 WRITE (6,175) AVG5,VAR5
      XM7=SUMA(66,1)
      XN7=SUMA(66,3)
      XS7=SUMA(66,2)
      AVG7=XM7/XN7
      VAR7=(((XN7*XS7)-(XM7*XM7))/(XN7*(XN7-1.0)))
      STD=SQRT(ABS(VAR7))
      WRITE (6,185) AVG7,STD
      XM7=SUMA(67,1)
      XN7=SUMA(67,3)
      XS7=SUMA(67,2)
      AVG7=XM7/XN7
      VAR7=(((XN7*XS7)-(XM7*XM7))/(XN7*(XN7-1.0)))
      STD=SQRT(ABS(VAR7))
      WRITE (6,186) AVG7,STD
      IF(MSW(5).GT.0) GO TO 17
      WRITE (6,180)
   17 CONTINUE
      XN=NTPDS
      DO 20 I=1,NM
      AB= SUMA(I,1)/FLOAT(NTPDS)
      WWW(I)=WWW(I)/FLOAT(NTPDS)
      WBM(I)=(WBM(I)*XN-SSUMA(I,2)**2)/(XN*(XN-1.0))
      IF(MSW(5).GT.0) GO TO 20
      WRITE (6,190) I,AB,WBM(I)
   20 CONTINUE
      TWB=0.0
      DO 30 I=1,NM
   30 TWB=TWB+WBM(I)/FLOAT(NM)
      SBM=(SUMA(14,2)*XN-SUMA(14,1)**2)/(XN*(XN-1.0))
      WRITE (6,200) TWB,SBM,NEN,NLV
      DO 40 I=12,14
      XS=SUMA(I,1)
      XSS=SUMA(I,2)
      XN=SUMA(I,3)
      AVGG=XS/XN
      VAR=(((XN*XSS)-(XS*XS))/(XN*(XN-1.0)))
      IF (I.EQ.12) PRINT 210, AVGG,VAR
      IF (I.EQ.13) PRINT 220, AVGG,VAR
      IF (I.EQ.14) AVGG=AVGG/PLEN*100.0
```

```
      IF (I.EQ.14) PRINT 230, AVGG
   40 CONTINUE
      DO 50 I=11,14
      XT=SSUMA(I,1)-TBEG
      XS=SSUMA(I,2)
      XSS=SSUMA(I,3)
      AVGG=XS/XT
      STD=(XSS/XT-AVGG*AVGG)
      STD=SIGN(SQRT(ABS(STD)),STD)
      IF (I.EQ.11) PRINT 240, AVGG,STD
      IF (I.EQ.12) PRINT 250, AVGG,STD
      IF (I.EQ.13) PRINT 252, AVGG,STD
      IF (I.EQ.14) PRINT 254, AVGG,STD
   50 CONTINUE
      TIME = FLOAT (NTPDS ) * PLEN
      PRINT 260, NTPDS,TIME
      IF(MSW(5).GT.0) GO TO 51
      PRINT 270, (I,WWW(I),I=1,NM)
   51 CONTINUE
      WRITE (6,361)
      WRITE (6,362)
      WRITE (6,363)
      QWB=0
      MAXQ=0
      XX=0
      NM1=NM+1
      DO 53 I=2,NM1
      XNQ=NQ(I)
      XE=(ENQ(I)+XNQ*(TNOW-QTIME(I)))/(TNOW-TBEG)
      VARE=((VNQ(I)+XNQ*XNQ*(TNOW-QTIME(I)))/(TNOW-TBEG)-XE*XE)
      IF (MAXNQ(I).GT.MAXQ) MAXQ=MAXNQ(I)
      IF(MSW(5).GT.0) GO TO 52
      I1=I-1
      WRITE (6,364) I1,XE,VARE,MAXNQ(I)
   52 CONTINUE
      XX=XX+XE
   53 QWB=QWB+VARE
      XX=XX/FLOAT(NM)
      QWB=QWB/FLOAT(NM)
      WRITE (6,365) XX,QWB,MAXQ
      PWB=SUMA(70,1)/SUMA(70,3)
      WRITE (6,367) PWB
      PQB=SUMA(71,1)/SUMA(71,3)
      WRITE (6,368) PQB
      WRITE (6,1911)
 1911 FORMAT (///)
      IST= 15
 1912 SUM = 0.0
      DO 1988 IIS = 1,10
      IIT = IST+ IIS
      XS = SUMA (IIT,1)
      XSS = SUMA (IIT,2)
      XN = SUMA (IIT,3)
      N = XN + .C01
      IF ( N-1)1982,1982,1983
 1982 VSTD = 0.0
      GO TO 1988
```

```
      1983 VSTD = (((XN*XSS)-(XS*XS))/(XN*(XN-1.0)))
      1988 SUM = SUM + VSTD
           ASUM = SUM/10.0
           IF ( IST .NE. 15 ) GO TO 1990
           WRITE (6,1989) ASUM
      1989 FORMAT(' VARIANCE OF MACHINE WAITING TIME' ,F12.3)
           IST = 71
           GO TO 1912
      1990 IF (IST .NE. 71) GO TO 1995
           WRITE (6,2001) ASUM
      2001 FORMAT (' VARIANCE OF MACHINE INTERARRIVAL TIMES ' , F12.3 )
           VSTD = 0.0
           VSTD =(((SUMA(82,3)*SUMA(82,2))-(SUMA(82,1)*SUMA(82,1)))/
          C (SUMA(82,3)*(SUMA(82,3)-1.0)))
           WRITE (6,2989) VSTD
      2989 FORMAT ( ' VARIANCE OF SHOP INTERARRIVAL TIMES ',F12.3)
           IST = 82
           GO TO 1912
      1995 IF (IST .NE. 82) GO  TO 1996
           WRITE (6,2002) ASUM
      2002 FORMAT ( ' VARIANCE OF WORK ARRIVED PER PERIOD ',F12.3)
           VSTD = 0.0
           VSTD=(((SUMA(93,3)*SUMA(93,2))-(SUMA(93,1)*SUMA(93,1)))/
          C (SUMA(93,3)*(SUMA(93,3)-1.0)))
           WRITE (6,3002) VSTD
      3002 FORMAT (' VARIANCE OF SHOP WORK ARRIVED PER PERIOD ', F12.3)
           IST = 93
           GO TO 1912
      1996 WRITE (6,2003) ASUM
      2003 FORMAT( ' VARIANCE OF OUTPUT PER PERIOD ',F12.3)
           VSTD = 0.0
           VSTD=(((SUMA(104,3)*SUMA(104,2))-(SUMA(104,1)*SUMA(104,1)))/
          C (SUMA(104,3)*(SUMA(104,3)-1.0)))
           WRITE (6,3003) VSTD
      3003 FORMAT( ' VARIANCE OF SHOP OUTPUT PER PERIOD ',F12.3)
           S = 0.0
           DO 2010 I =15,24
           XT = SSUMA(I,1)-TBEG
           XS = SSUMA(I,2)
           XSS = SSUMA (I,3)
           AVG = XS/XT
      2010 S =(XSS/XT-AVG*AVG)+S
           ASS = S/10.0
           WRITE (6,2009) ASS
      2009 FORMAT(' VARIANCE OF QUEUE LENGTH IN HOURS OF WORK ',F12.3)
           IF ( NRUN .GT. 1) GO TO 69
           IF(MSW(5).GT.0) GO TO 69
           PRINT 280
           DO 60 I=1,NM
        60 WRITE (6,290) (X(I,J),J=1,NM)
           WRITE (6,300)
           WRITE (6,310) IDUE,    ITYPE,SEED,ISEED,NLDR
           RRATE=1.0/ARATE
           WRITE (6,320) ARATE
           WRITE (6,321) RRATE
           XM6=SUMA(65,1)
           XN6=SUMA(65,3)
```

```
      AVG6=XM6/XN6
      WRITE (6,322) AVG6
      WRITE (6,330) NPREL,NPREP,NDESL,DESLF
      WRITE (6,335) NDML,DMLF,NARR
      WRITE (6,336) FACDUD,SINPER
      WRITE (6,340)
      WRITE (6,290) (TIMEF(J),J=1,NM)
      WRITE (6,345)
      WRITE (6,290) (CAPM(J),J=1,NM)
      WRITE (6,350)
      WRITE (6,290) (DESL(J),J=1,NM)
      WRITE (6,355)
      WRITE (6,290) (DQL(J),J=1,NM)
C
C     ***  SET UP FOR NEXT RUN. CHANGE DISPATCHING RULE.
C     ***  INITIALIZE STATUS VARIABLES.
C
   69 NRULE=NRULE+1
C     ***  IT IS DESIRED TO SKIP RULE 5 (DUE DATE)
      IF (NRULE.EQ.5) NRULE=6
      IF (NRULE.LE.4) GO TO 120
      IF (NRULE.GT.5) GO TO 80
      DO 70 I=2,11
   70 KRANK(I)=4
      GO TO 120
   80 IF (NRULE.GT.6) GO TO 150
      DO 90 I=2,11
   90 KRANK(I)=8
      GO TO 120
  120 CONTINUE
      DO 130 I=1,NM
      AR(I)=0.0
      WB(I)=0.0
      WBM(I)=0.0
      WWW(I)=0.0
      BUS(I)=0.0
      SHOPLD(I)=0.0
 130  QLOAD(I)=0.0
      MAX=0
      DO 140 I=1,200
  140 LOC(I)=0
C*******THIS IS IS TO ZERO THE ARR SUM ARRAY
      DO 145 I= 1,35
  145 ARS(I)=0.0
      AR(11)=0.0
      XOPS=0.0
      XWKS=0.0
      XISYS=0.0
      XWKSY=0.0
      NEN=0
      NLV=0
      NPOOLB=0
      NPOOLA=0
      NHELD=0
      NTPDS=0
      XXSD=DRAND(ISEED)
      NRST=NRSET
```

```
  150 MSTOP=-1
      RETURN
  160 FORMAT (1H1, 36HVARIOUS APPROACHES FOR JOB SHOP LOAD
     1,37HING USING DIFFERENT DISPATCHING RULES,/20X,3H LO
     2,21HADING APPROACH NUMBER,I5,/20X,15HDISPATCHING RUL
     3,9HE NUMBER ,I4///)
  172 FORMAT (1H ////5X,7HMACHINE, 13X,16HDEVIATION FROM B
     1,6HALANCE,/21X,14HAGGREGATE LOAD,14X,10HQUEUE LOAD)
  173 FORMAT (5X,I6,10X,F12.3,4X,F12.3)
  174 FORMAT (/5X,37HDEVIATION FROM BALANCE,AGGREGATE LOAD)
  175 FORMAT (1H ,5X,7HAVERAGE,2X,F10.3,8HVARIANCE,5X,F10.3)
  176 FORMAT (/5X,33HDEVIATION FROM BALANCE,QUEUE LOAD)
  177 FORMAT (///5X,24HTIME SPENT IN THE SYSTEM)
  178 FORMAT (/5X,26HTIME SPENT IN THE JOB POOL)
  179 FORMAT (/5X,38HTIME SPENT IN THE SYSTEM W/O POOL TIME)
  252 FORMAT (10X, 37HW.I.P.(AVERAGE OPERATIONS PERFORMED P
     120HER JOB IN THE SHOP),/15X,5HAVG= ,F10.3,6H   STD=,F10.3)
  254 FORMAT(10X,39HW.I.P.(AVERAGE HOURS OF WORK DONE FOR J
     117HOBS IN THE SHOP),/15X,5HAVG= ,F10.3,6H  STD=,F10.3)
  170 FORMAT (5X, 37H NUMBER OF MACHINES IN THE SIMULATED
     15HSHOP ,I6/5X,26H NUMBER OF RUN IN PERIODS ,I8/5X,
     246H NUMBER OF TIME PERIODS SIMULATED AFTER RUN IN,
     3I6/5X, 28H LENGTH OF EACH TIME PERIOD ,F8.2)
  171 FORMAT (1H ,5X,16HSPECIAL FEATURES,4X,10I1)
  180 FORMAT (1H1////5X,  7HMACHINE, 18H  UTILIZATION BAL
     1,12HANCE MEASURE)
  185 FORMAT (//1H ,37HJOBS IN THE POOL BEFORE LOADING  AVG ,
     1F7.2,6H  STD ,F7.2)
  186 FORMAT (//1H ,37HJOBS IN THE POOL AFTER  LOADING  AVG ,
     1F7.2,6H  STD ,F7.2)
  190 FORMAT (5X,I6,F12.3,F14.3)
  200 FORMAT (///10X, 25HMACHINE BALANCE MEASURE =,F12.3/
     110X, 22HSHOP BALANCE MEASURE =,F12.3/10X,
     230HNUMBER OF JOBS ENTERING SHOP =,I7/10X,
     329HNUMBER OF JOBS LEAVING SHOP = ,I7)
  210 FORMAT (10X, 23HAVERAGE JOB LATENESS = ,F10.2/10X,
     128HAVERAGE LATENESS VARIANCE = ,F10.2)
  220 FORMAT (10X, 23HAVERAGE JOB TARDINESS =,F12.3/10X,
     1 28HAVERAGE TARDINESS VARIANCE =,F12.3)
  230 FORMAT (10X,26HAVERAGE SHOP UTILIZATION =,F12.3)
  240 FORMAT (10X, 34HAVERAGE W.I.P.(IN HOURS OF WORK) =,
     1F12.3,1X,F14.3)
  250 FORMAT (10X, 34HAVERAGE NUMBER OF JOBS IN THE SHOP,
     12H =,F12.3,F12.3)
  260 FORMAT (10X, 29HLENGTH OF SIMULATION RUN WAS ,/10X,
     1I5, 15H  TIME PERIODS , 1H(,F10.1,  9H HOURS ) )
  270 FORMAT (/////15X, 7HMACHINE,3X, 13HAVG INPUT/PD./
     1(15X,I4,8X,F7.2))
  280 FORMAT (1H1//9X, 32HTHE JOB SHOP PROBABILITY TRANSIT
     1,10HION MATRIX,////)
  290 FORMAT (3X,10F6.3)
  300 FORMAT (//////, 34H     IDUE        000      ITYPE
     1,23H  SEED     ISEED   NLOR)
  310 FORMAT (/5X,I4,4X,7X,5X,I5,2X,F10.4,3X,I8,I4)
  320 FORMAT (/5X, 26HMEAN INPUT ARRIVAL RATE = ,F7.4,
     1 16H ARRIVALS/HOUR  )
  321 FORMAT (5X,29HMEAN TIME BETWEEN ARRIVALS = ,F7.4,
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```
      18H    HOURS)
  322 FORMAT (5X,36HACTUAL MEAN TIME PER OPERATION    =
     1F7.4,7H  HOURS)
  330 FORMAT (1H //3X,7HNPREL= ,I5,3X,7HNPREP= ,I5,3X,3HNDE
     14HSL= ,I5,3X,7HDESLF= ,F10.3)
  335 FORMAT (1H ,3X,6HNDML= ,I5,3X,6HDMLF= ,F10.3,3X,3HNAR
     13HR= ,I5)
  336 FORMAT (1H ,3X,8HFACDUD= ,F8.2,3X,8HSINPER= ,F9.2)
  340 FORMAT (1H ///5X,33HJOB OPERATION TIME FACTORS FOR EA
     110HCH MACHINE)
  345 FORMAT (1H ///10X,32HMACHINE CENTER CAPACITIES PER PE
     14HRIOD)
  350 FORMAT (1H ///10X,34HDESIRED AGGREGATE LOAD PER MACHINE)
  355 FORMAT (1H //10X,30HDESIRED QUEUE LOAD PER MACHINE)
  361 FORMAT (///5X,22HOTHER BALANCE MEASURES/)
  362 FORMAT (/5X,27HMACHINE QUEUE BALANCE INDEX)
  363 FORMAT (3X,7HMACH NO,7X,7HAVERAGE,12X,3HQWB,8X,7HMAXIMUM)
  364 FORMAT (5X,I4,2F15.3,10X,I5)
  365 FORMAT (/5X,4H ALL,2F15.3,10X,I5)
  367 FORMAT (/5X,25HPERIOD WORK BALANCE INDEX,4X,6HPWB = ,F9.3)
  368 FORMAT (/5X,26HPERIOD QUEUE BALANCE INDEX,4X,6HPQB = ,F9.2)
      END
@PRT SHOPQUEUE.PTJOB
```

```
BELLER-RICHA*SHOPQUEUE,PTJOB
      SUBROUTINE PTJOB (INP,NSET)
C
C     ***  SUBROUTINE WHICH MOVES JOB TO NEXT MACHINE
C     ***  CENTER
C
      DIMENSION NSET(35,1)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,
     2ISEED,TNOW,TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(25),
     3KOF,KLE,KOL,ATRIB(33),ENQ(25),INN(25),JCELS(20,32),
     4KRANK(25),JCLR,MAXNQ(25),MFE(25),MLC(25),MLE(25),
     5 NCELS(20),NQ(25),PARAM(40,4),QTIME(25),SSUMA(35,5)
     6,SUMA(130,5),NAME(6),NPROJ,MON,NDAY,NYR
     1,ARS(35)
      COMMON PLEN,NTPDS,NTOTPD,NM,XISYS,XWKSY,IDUE,
     1ITYPE,MNEXT,NEN,NLV,NHELD,WB(10),WBM(10),X(10,10),
     2         BUS(10),NRSET,NRULE,MNOW,NRST,NENDS,NHOL,NRL,
     3WWW(10),SEED,ARATE,LOC(200),MAX,AR(11)
      COMMON NPREL,NPREP,NDESL,NDML,CAPM(10),DESL(10),
     1DQL(10),DESLF,DMLF,QLOAD(10),XOPS,XWKS,TIMEF(10),
     2NSTSW,NLDR,NARR,SHOPLD(10)
      COMMON A(25,200),KBV(15),C(200),FACDUD
      COMMON ICOUNT,NCOUNT,SINPER,MSW(10),AVGLD9
C
C     ***  CHECK IF JOB IS A NEW ARRIVAL
C
      IF (INP.NE.1) GO TO 10
      ATRIB(3)=TNOW
      NEN=NEN+1
C
C     ***  NEW ARRIVAL. CHECK IF A JOB POOL IS BEING USED
C
      IF (NLDR.EQ.0) GO TO 20
C
C     ***  CHECK IF SHOP IS BEING PRELOADED AND JOB POOL
C     ***  HAS BEEN COMPLETED
C
      IF (NSTSW.EQ.1) GO TO 20
C
C     ***  PUT ARRIVING JOB IN THE POOL IF OP. 1 MACH IS NOT IDLE
C
      ATRIB(8)=TNOW
      JOB=ATRIB(30)+0.001
      LOC(JOB)=MFA
C
C     ***  COLLECT STATISTICS ON INTERARRIVAL TIMES TO
C     ***  THE JOB POOL
C
      D=TNOW-AR(11)
      CALL HISTO (D,0.5,0.5,15,NSET)
      AR(11)=TNOW
      NFIRST=ATRIB(11)+0.00001
      IF (MSW(1).EQ.0) GO TO 4
      IF (TNOW.LE.0.0001) GO TO 4
      IF (BUS(NFIRST)) 5,5,4
    4 CALL FILEM(12,NSET)
```

```
      GO TO 70
C
C     ***  IF FIRST OPERATION MACHINE IS IDLE,CONSIDER THE
C     ***  JOB AS COMING FROM POOL AND PUT IN THE SHOP
C
    5 CONTINUE
      IF (MSW(3).EQ.0) GO TO 6
      IF(SSUMA(NFIRST,3).GE.AVGLD9) GO TO 4
    6 MNEXT=NFIRST
      CALL COLCT (1.0,69,NSET)
      GO TO 20
C
C     ***  JOB IS NOT A NEW ARRIVAL. CHECK IF IT IS COMING
C     ***  FROM THE POOL
C
   10 IF (INP.EQ.2) GO TO 40
C
C     ***  JOB IS COMING FROM THE POOL.
C     ***  ALSO NEW JOBS WHEN A POOL IS NOT USED ARRIVE
C     ***  AT THIS POINT
C     ***  UPDATE STATUS OF WORK IN SHOP AND ALSO UPDATE
C     ***  AGGREGATE LOAD IN SHOP QUEUES FOR EACH MACHINE.
C
   20 CALL TMST (XISYS,TNOW,12,NSET)
      CALL TMST (XWKSY,TNOW,11,NSET)
      XISYS=XISYS+1.0
      XWKSY=XWKSY+ATRIB(9)
      ATRIB(33)=TNOW
      NNN=9.0+2.*ATRIB(10)+.00001
      DO 37 I=11,NNN,2
      J=ATRIB(I)
   37 SHOPLD(J)=SHOPLD(J)+ATRIB(I+1)
C
C     ***  JOB IS NOT GOING INTO THE POOL. COLLECT STATISTICS
C     ***  ON INTERARRIVAL TIMES TO THE CURRENT MACHINE
C
   40 D=TNOW-AR(MNEXT)
      MN4=MNEXT+4
C*****
C***** COLLECT DATA ON THE INTERARRIVAL TIMES TO THE SHOP
C***** COLLECT DATA ON THE INTERARRIVAL TIMES TO A MACHINE
C*****
      M72 = MNEXT + 71
      CALL COLCT (D,M72,NSET)
      CALL COLCT ( D,82,NSET)
      ARS(MNEXT)=ARS(MNEXT)+ATRIB(12)
      ARS(11)=ARS(11)+ATRIB(12)
      CALL HISTO (D,0.5,0.5,MN4,NSET)
      AR(MNEXT)=TNOW
C
C     ***  CHECK ON THE STATUS OF MACHINE FOR NEXT
C     ***  JOB OPERATION
C
      IF (BUS(MNEXT)) 60,60,50
C
C     ***  NEXT MACHINE IS BUSY. JOB CAN NOT BE PUT ON
C          MACHINE
```

```
C
   50 ATRIB(8)=TNOW
      MX1=MNEXT+1
      JOB=ATRIB(30)+0.001
      LOC(JOB)=MFA
      QLOAD(MNEXT)=QLOAD(MNEXT)+ATRIB(12)
C*****
C***** HOURS OF WORK IN QUEUE I
C*****
      M15=14+MNEXT
      MOLD=MNEXT+11
      XXX=ARS(MOLD)
      CALL TMST(XXX,TNOW,M15,NSET)
      ARS(MOLD)=ARS(MOLD)+ATRIB(12)
      CALL FILEM (MX1,NSET)
      GO TO 70
C
C     ***  NEXT MACHINE IS NOT BUSY.
C     ***  JOB MAY BE PUT ON MACHINE
C
   60 CALL TMST (BUS(MNEXT),TNOW,MNEXT,NSET)
      BUS(MNEXT)=1.0
      WT=0.0
      MX15=MNEXT+15
      CALL COLCT (WT,MX15,NSET)
      TIMEVT=ATRIB(12) *(8.0/CAPM(MNEXT))
      ATRIB(1)=TNOW+TIMEVT
      ATRIB(2)=1.0
      J=ATRIB(11)
      SHOPLD(J)=SHOPLD(J)-ATRIB(12)
      JOB=ATRIB(30)+0.001
      LOC(JOB)=MFA
      CALLFILEM  (1,NSET)
   70 NSTSW=0
      RETURN
      END
@FIN
```

APPENDIX E

SAMPLE LISTING OF SIMULATION OUTPUT

```
VARIOUS APPROACHES FOR JOB SHOP LOADING USING DIFFERENT DISPATCHING RULES
                    LOADING APPROACH NUMBER    0
                   DISPATCHING RULE NUMBER    1


   NUMBER OF MACHINES IN THE SIMULATED SHOP      10
   NUMBER OF RUN IN PERIODS          50
   NUMBER OF TIME PERIODS SIMULATED AFTER RUN IN    500
   LENGTH OF EACH TIME PERIOD      8.00
   SPECIAL FEATURES     0000000000


  MACHINE                 DEVIATION FROM BALANCE
                     AGGREGATE LOAD                  QUEUE LOAD
       1                     9.557          -5.814
       2                     4.989          -8.927
       3                    13.192          -4.721
       4                     8.532          -7.858
       5                    10.519          -5.717
       6                     8.616          -6.312
       7                     5.974          -8.405
       8                    12.213          -3.318
       9                    11.751          -5.033
      10                    12.098          -5.549

  DEVIATION FROM BALANCE,AGGREGATE LOAD
   AVERAGE      171.367VARIANCE         4140.554

  DEVIATION FROM BALANCE,QUEUE LOAD
   AVERAGE       69.745VARIANCE          639.088


  TIME SPENT IN THE SYSTEM
   AVERAGE       65.636VARIANCE         1416.966

  TIME SPENT IN THE JOB POOL
   AVERAGE         .000VARIANCE             .000

  TIME SPENT IN THE SYSTEM W/O POOL TIME
   AVERAGE       65.636VARIANCE         1416.966

JOBS IN THE POOL BEFORE LOADING  AVG     .00  STD     .00

JOBS IN THE POOL AFTER  LOADING  AVG     .00  STD     .00
```

MACHINE	UTILIZATION	BALANCE MEASURE
1	84.056	4.698
2	84.294	4.593
3	76.999	5.769
4	83.654	4.673
5	80.696	4.731
6	83.769	4.617
7	85.457	4.120
8	77.269	5.622
9	77.564	5.848
10	79.094	5.329

MACHINE BALANCE MEASURE = 5.000
SHOP BALANCE MEASURE = .641
NUMBER OF JOBS ENTERING SHOP = 2111
NUMBER OF JOBS LEAVING SHOP = 2114
AVERAGE JOB LATENESS = -26.46
AVERAGE LATENESS VARIANCE = 798.31
AVERAGE JOB TARDINESS = 1.189
AVERAGE TARDINESS VARIANCE = 12.377
AVERAGE SHOP UTILIZATION = 81.285
AVERAGE W.I.P.(IN HOURS OF WORK) = 570.955 171.421
AVERAGE NUMBER OF JOBS IN THE SHOP = 34.613 10.544
W.I.P.(AVERAGE OPERATIONS PERFORMED PER JOB IN THE SHOP).
AVG= 71.682 STD= 20.271
W.I.P.(AVERAGE HOURS OF WORK DONE FOR JOBS IN THE SHOP).
AVG= 168.473 STD= 55.522
LENGTH OF SIMULATION RUN WAS
500 TIME PERIODS (4000.0 HOURS)

MACHINE	AVG INPUT/PD.
1	84.20
2	84.73
3	77.44
4	84.10
5	81.00
6	83.90
7	85.76
8	77.80
9	77.92
10	79.42

OTHER BALANCE MEASURES

MACHINE QUEUE BALANCE INDEX

MACH NO	AVERAGE	QWB	MAXIMUM
1	2.578	7.138	15
2	3.585	15.376	17
3	2.179	12.603	21
4	3.135	15.900	21
5	2.533	9.825	14
6	2.788	9.734	15
7	3.685	19.791	22
8	1.599	4.351	12
9	2.218	8.010	16
10	2.205	8.456	15
ALL	2.650	11.118	22

PERIOD WORK BALANCE INDEX PWB = 4.414

PERIOD QUEUE BALANCE INDEX PQB = 26.94

VARIANCE OF MACHINE WAITING TIME 250.409
VARIANCE OF MACHINE INTERARRIVAL TIMES 9.825
VARIANCE OF SHOP INTERARRIVAL TIMES 9.814
VARIANCE OF WORK ARRIVED PER PERIOD 27.264
VARIANCE OF SHOP WORK ARRIVED PER PERIOD 269.595
VARIANCE OF OUTPUT PER PERIOD 1.965
VARIANCE OF SHOP OUTPUT PER PERIOD 26.268
VARIANCE OF QUEUE LENGTH IN HOURS OF WORK 66.939

THE JOB SHOP PROBABILITY TRANSITION MATRIX

.100	.200	.300	.400	.500	.600	.700	.800	.900	1.000
.100	.200	.300	.400	.500	.600	.700	.800	.900	1.000
.100	.200	.300	.400	.500	.600	.700	.800	.900	1.000
.100	.200	.300	.400	.500	.600	.700	.800	.900	1.000
.100	.200	.300	.400	.500	.600	.700	.800	.900	1.000
.100	.200	.300	.400	.500	.600	.700	.800	.900	1.000
.100	.200	.300	.400	.500	.600	.700	.800	.900	1.000
.100	.200	.300	.400	.500	.600	.700	.800	.900	1.000
.100	.200	.300	.400	.500	.600	.700	.800	.900	1.000
.100	.200	.300	.400	.500	.600	.700	.800	.900	1.000

IDUE	000	ITYPE	SEED	ISEED	NLDR
1		1	.0000	349387	0

MEAN INPUT ARRIVAL RATE = .5300 ARRIVALS/HOUR
MEAN TIME BETWEEN ARRIVALS = 1.8868 HOURS
ACTUAL MEAN TIME PER OPERATION = 2.5859 HOURS

NPREL= 45 NPREP= 25 NDESL= 1 DESLF= 6.000
NDML= 1 DMLF= .400 NARR= 2
FACDUD= 80.00 SINPEP= 16.00

JOB OPERATION TIME FACTORS FOR EACH MACHINE
1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000

MACHINE CENTER CAPACITIES PER PERIOD
8.000 8.000 8.000 8.000 8.000 8.000 8.000 8.000 8.000 8.000

DESIRED AGGREGATE LOAD PER MACHINE
48.00048.00048.00048.00048.00048.00048.00048.00048.00048.000

DESIRED QUEUE LOAD PER MACHINE
3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200

THE FIRST CARD NOT READ DURING EXECUTION WAS:
0 1 0 7 0.000 10.0005909
103 ADDITIONAL CARDS WERE NOT READ.

APPENDIX F

RESULTS OF SIMULATION RUNS

Table 15. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.25	81.53	81.33	81.29	81.08	81.30
2. Average Number of Jobs in Shop	37.50	37.21	36.11	34.61	36.54	36.39
3. Average Number of Operations for Jobs in the Shop	74.24	74.28	73.18	71.68	73.30	73.34
4. Average Work (Hours) Done for Jobs in Shop	176.01	175.73	173.08	168.47	173.20	173.30
5. Average Work in Process (Hours)	617.44	611.64	595.56	570.96	602.86	599.69
6. Time Spent in the System	71.39	70.40	68.55	65.64	69.46	69.09
7. Time Spent in the Shop	71.39	70.40	68.55	65.64	69.46	69.09
8. Average Job Tardiness	2.07	1.93	1.63	1.19	1.86	1.74
9. Variance of Job Tardiness, Average	26.15	23.94	18.05	12.38	21.90	20.48
10. Average Lateness	-20.82	-21.78	-23.47	-26.46	-22.67	-23.04
11. Variance of Lateness, Average	765.88	760.00	794.65	798.31	805.16	784.80
12. Machine Balance Measure	5.183	4.98	5.10	5.00	5.21	5.09
13. Shop Balance Measure	.730	.78	.73	.64	.75	.73
14. Queue Workload Balance	13.72	12.19	12.60	11.12	12.75	12.48
15. Period Queue Balance	37.67	61.11	26.45	26.94	19.54	34.54
16. Variance of Waiting Time Per Operation, Average	310.90	287.45	281.42	250.41	289.01	283.84
17. Average Queue Length in Number of Jobs (Shop)	2.94	2.91	2.80	2.65	2.84	2.83
18. Variance of Queue Length in Hours of Work, Average (Machine)	104.84	91.94	99.25	87.27	100.65	96.79
19. Variance of Interarrival Times, Average (Machine)	9.89	9.80	10.36	9.83	10.30	10.04
20. Variance of Interarrival Times (Shop)	9.87	9.78	10.34	9.81	10.28	10.02
21. Variance of Work Arrived Per Period, Average (Machine)	27.22	27.98	27.72	27.27	28.07	27.65
22. Variance of Work Arrived Per Period (Shop)	299.77	275.37	292.33	269.60	297.02	286.82
23. Variance of Output, Average Machine	2.03	1.95	2.03	1.97	2.05	2.01
24. Variance of Output (Shop)	27.91	26.91	29.11	26.27	31.89	28.42

Conditions: Low Utilization, No Pool, Dynamic Slack (1)

Table 16. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.47	81.70	81.22	81.09	81.91	81.48
2. Average Number of Jobs in Shop	38.59	38.20	37.68	38.10	37.65	38.04
3. Average Number of Operations for Jobs in the Shop	92.57	95.60	93.73	95.21	93.19	94.06
4. Average Work (Hours) Done for Jobs in Shop	222.57	232.13	225.46	230.25	224.60	227.00
5. Average Work in Process (Hours)	626.81	621.34	612.59	621.85	615.55	619.63
6. Time Spent in the System	73.32	72.22	71.86	72.23	71.25	72.18
7. Time Spent in the Shop	73.32	72.22	71.86	72.23	71.25	72.18
8. Average Job Tardiness	2.14	1.26	1.22	1.67	1.54	1.57
9. Variance of Job Tardiness, Average	35.21	15.15	15.15	20.02	19.06	20.92
10. Average Lateness	-18.90	-19.92	-20.38	-19.79	-20.98	-19.99
11. Variance of Lateness, Average	848.27	741.21	744.32	802.70	854.56	798.21
12. Machine Balance Measure	5.25	5.09	5.22	5.12	5.03	5.14
13. Shop Balance Measure	1.04	.91	1.04	.92	.89	.96
14. Queue Workload Balance	13.92	13.62	13.41	14.78	13.80	13.91
15. Period Queue Balance	50.27	76.51	34.36	38.02	48.76	49.58
16. Variance of Waiting Time Per Operation, Average	299.23	284.66	277.31	288.56	287.42	287.44
17. Average Queue Length in Number of Jobs (Shop)	3.05	3.00	2.96	3.00	2.95	2.99
18. Variance of Queue Length in Hours of Work, Average (Machine)	103.66	103.32	99.92	111.28	107.22	105.08
19. Variance of Interarrival Times, Average (Machine)	10.59	10.21	10.57	10.20	10.13	10.34
20. Variance of Interarrival Times (Shop)	10.57	10.23	10.56	10.19	10.11	10.33
21. Variance of Work Arrived Per Period, Average (Machine)	27.70	27.79	27.35	27.12	27.53	27.50
22. Variance of Work Arrived Per Period (Shop)	369.97	322.01	336.59	302.23	300.25	326.21
23. Variance of Output, Average Machine	2.09	2.06	2.06	2.03	2.02	2.05
24. Variance of Output (Shop)	35.01	30.52	32.61	31.18	31.04	32.07

Conditions: Low Utilization, No Pool, Dynamic Slack Per Operation (2)

Table 17. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.62	81.56	81.17	81.15	81.11	81.32
2. Average Number of Jobs in Shop	33.21	32.86	32.67	32.54	33.23	32.90
3. Average Number of Operations for Jobs in the Shop	108.94	107.59	107.10	105.17	109.06	107.57
4. Average Work (Hours) Done for Jobs in Shop	257.69	257.03	258.59	253.58	262.69	257.92
5. Average Work in Process (Hours)	552.47	549.90	549.45	544.57	556.26	550.92
6. Time Spent in the System	63.29	62.88	63.75	62.12	63.13	63.03
7. Time Spent in the Shop	63.29	62.88	63.75	62.12	63.13	63.03
8. Average Job Tardiness	12.95	13.07	13.66	12.25	12.60	12.91
9. Variance of Job Tardiness, Average	1239.04	1254.22	1594.76	1028.39	1009.91	1225.26
10. Average Lateness	-28.87	-29.25	-28.34	-29.98	-29.03	-29.09
11. Variance of Lateness, Average	4048.24	4056.33	4433.78	3750.91	3719.21	4001.69
12. Machine Balance Measure	5.44	5.184	5.37	5.44	5.50	5.39
13. Shop Balance Measure	1.53	1.13	1.46	1.62	1.62	1.47
14. Queue Workload Balance	8.73	9.43	9.19	8.31	9.00	8.93
15. Period Queue Balance	65.71	106.29	48.05	42.97	16.41	55.89
16. Variance of Waiting Time Per Operation, Average	394.28	395.75	465.50	348.31	360.99	392.97
17. Average Queue Length in Number of Jobs (Shop)	2.51	2.47	2.46	2.44	2.51	2.48
18. Variance of Queue Length in Hours of Work, Average (Machine)	90.57	99.95	95.23	86.81	88.16	92.14
19. Variance of Interarrival Times, Average (Machine)	10.88	9.92	10.34	10.48	10.60	10.44
20. Variance of Interarrival Times (Shop)	10.87	9.88	10.32	10.46	10.57	10.42
21. Variance of Work Arrived Per Period, Average (Machine)	26.94	26.39	25.90	26.19	26.00	26.28
22. Variance of Work Arrived Per Period (Shop)	450.36	353.83	419.58	449.07	437.01	421.97
23. Variance of Output, Average Machine	2.10	2.01	2.11	2.10	2.07	2.08
24. Variance of Output (Shop)	43.84	34.18	42.27	41.57	42.40	40.85

Conditions: Low Utilization, No Pool, Expected Work in Next Queue (3)

Table 18. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.63	81.52	81.63	81.20	81.47	81.49
2. Average Number of Jobs in Shop	24.79	25.32	26.10	24.71	24.75	25.13
3. Average Number of Operations for Jobs in the Shop	63.70	65.29	66.98	63.67	64.44	64.82
4. Average Work (Hours) Done for Jobs in Shop	145.89	150.31	154.18	145.03	147.25	148.63
5. Average Work in Process (Hours)	460.53	473.49	489.26	459.66	458.51	468.29
6. Time Spent in the System	47.69	48.82	50.62	47.09	46.78	48.20
7. Time Spent in the Shop	47.69	48.82	50.62	47.09	46.78	48.20
8. Average Job Tardiness	7.01	8.13	8.68	6.61	6.28	7.34
9. Variance of Job Tardiness, Average	629.33	816.70	1125.43	534.05	464.64	714.03
10. Average Lateness	-44.47	-43.30	-41.66	-45.05	-45.27	-43.95
11. Variance of Lateness, Average	3200.08	3503.52	3850.73	3060.41	2963.93	3315.73
12. Machine Balance Measure	5.18	5.30	5.35	5.40	5.23	5.29
13. Shop Balance Measure	.93	1.21	1.33	1.40	1.10	1.19
14. Queue Workload Balance	3.60	3.79	4.05	3.38	3.61	3.69
15. Period Queue Balance	16.00	45.16	17.81	14.17	6.75	19.98
16. Variance of Waiting Time Per Operation, Average	207.18	265.26	326.68	205.88	191.49	239.30
17. Average Queue Length in Number of Jobs (Shop)	1.66	1.72	1.79	1.66	1.66	1.70
18. Variance of Queue Length in Hours of Work, Average (Machine)	125.91	141.12	156.92	117.10	126.36	133.48
19. Variance of Interarrival Times, Average (Machine)	10.57	10.67	10.94	11.23	10.62	10.81
20. Variance of Interarrival Times (Shop)	10.55	10.64	10.91	11.15	10.60	10.77
21. Variance of Work Arrived Per Period, Average (Machine)	27.97	28.84	28.30	28.87	28.44	28.48
22. Variance of Work Arrived Per Period (Shop)	402.49	450.24	468.19	459.54	434.59	443.01
23. Variance of Output, Average Machine	1.94	1.97	1.98	2.05	1.96	1.98
24. Variance of Output (Shop)	40.02	44.06	47.96	47.77	42.31	44.42

Conditions: Low Utilization, No Pool, Shortest Processing Time (4)

Table 19. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.27	81.52	81.16	81.28	81.12	81.27
2. Average Number of Jobs in Shop	24.90	24.98	24.78	24.72	25.14	24.90
3. Average Number of Operations for Jobs in the Shop	64.09	64.56	64.48	63.23	65.63	64.40
4. Average Work (Hours) Done for Jobs in Shop	146.10	148.76	147.79	144.99	151.82	147.89
5. Average Work in Process (Hours)	462.65	465.56	462.14	457.90	469.42	463.53
6. Time Spent in the System	47.67	47.25	47.18	46.92	47.84	47.37
7. Time Spent in the Shop	47.67	47.25	47.18	46.92	47.84	47.37
8. Average Job Tardiness	6.91	6.60	6.53	6.48	6.93	6.69
9. Variance of Job Tardiness, Average	567.10	536.60	474.41	521.55	541.07	528.15
10. Average Lateness	-44.50	-44.83	-44.92	-45.18	-44.24	-44.73
11. Variance of Lateness, Average	3103.47	2096.28	2986.31	3029.95	3086.38	2060.48
12. Machine Balance Measure	5.39	5.28	5.37	5.29	5.52	5.37
13. Shop Balance Measure	1.30	1.28	1.27	.98	1.32	1.23
14. Queue Workload Balance	3.47	3.69	3.58	3.70	3.61	3.61
15. Period Queue Balance	12.47	17.00	7.93	10.79	5.04	10.65
16. Variance of Waiting Time Per Operation, Average	204.68	211.68	192.84	202.00	200.37	202.31
17. Average Queue Length in Number of Jobs (Shop)	1.68	1.68	1.67	1.66	1.70	1.68
18. Variance of Queue Length in Hours of Work, Average (Machine)	121.50	132.77	128.79	132.33	126.31	128.34
19. Variance of Interarrival Times, Average (Machine)	11.02	10.81	10.77	10.54	11.18	10.86
20. Variance of Interarrival Times (Shop)	11.00	10.78	10.75	10.53	11.15	10.84
21. Variance of Work Arrived Per Period, Average (Machine)	27.95	28.29	28.66	27.76	28.74	28.28
22. Variance of Work Arrived Per Period (Shop)	447.92	457.27	443.09	393.01	474.933	443.24
23. Variance of Output, Average Machine	1.96	1.99	1.91	1.88	2.00	1.95
24. Variance of Output (Shop)	44.98	43.46	45.87	36.13	48.23	43.73

Conditions: Low Utilization, No Pool, Due Date (5)

Table 20. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.26	81.34	81.74	81.34	81.23	81.38
2. Average Number of Jobs in Shop	37.22	38.21	37.69	38.99	37.55	37.93
3. Average Number of Operations for Jobs in the Shop	97.34	100.32	98.33	102.59	98.42	99.40
4. Average Work (Hours) Done for Jobs in Shop	234.88	242.67	237.76	249.10	238.42	240.57
5. Average Work in Process (Hours)	619.63	636.13	628.12	650.39	624.24	631.70
6. Time Spent in the System	70.81	72.63	71.18	74.37	71.23	72.04
7. Time Spent in the Shop	70.81	72.63	71.18	74.37	71.23	72.04
8. Average Job Tardiness	12.78	13.40	12.63	14.28	12.70	13.16
9. Variance of Job Tardiness, Average	565.26	608.14	542.54	670.28	556.11	588.47
10. Average Lateness	-21.29	-19.47	-21.08	-17.76	-20.90	-20.10
11. Variance of Lateness, Average	2824.60	2850.79	2775.19	2944.88	2768.67	2832.83
12. Machine Balance Measure	5.19	5.25	4.97	5.31	5.17	5.18
13. Shop Balance Measure	.97	.99	.68	1.00	.96	.92
14. Queue Workload Balance	13.20	13.78	13.72	13.91	13.77	13.58
15. Period Queue Balance	61.96	128.93	65.77	74.20	25.60	71.29
16. Variance of Waiting Time Per Operation, Average	105.26	109.41	109.18	109.15	111.44	108.89
17. Average Queue Length in Number of Jobs (Shop)	2.91	3.01	2.95	3.09	2.94	2.98
18. Variance of Queue Length in Hours of Work, Average (Machine)	100.32	104.05	104.28	104.12	105.84	103.72
19. Variance of Interarrival Times, Average (Machine)	10.00	10.43	9.96	10.42	10.27	10.22
20. Variance of Interarrival Times (Shop)	9.98	10.41	9.95	10.40	10.25	10.20
21. Variance of Work Arrived Per Period, Average (Machine)	27.35	28.29	28.10	27.63	28.19	27.91
22. Variance of Work Arrived Per Period (Shop)	337.83	334.99	313.99	354.47	326.06	333.47
23. Variance of Output, Average Machine	2.03	1.98	2.06	2.06	1.99	2.02
24. Variance of Output (Shop)	32.29	31.22	28.60	33.01	31.76	31.38

Conditions: Low Utilization, No Pool, First Come First Served (6)

Table 21. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.02	81.32	81.16	80.82	81.07	81.08
2. Average Number of Jobs in Shop	30.92	31.74	31.34	30.77	31.65	31.28
3. Average Number of Operations for Jobs in the Shop	67.96	67.71	68.46	67.35	68.42	67.98
4. Average Work (Hours) Done for Jobs in Shop	158.59	159.41	160.75	157.59	161.82	159.63
5. Average Work in Process (Hours)	500.92	513.08	506.39	499.70	513.13	506.64
6. Time Spent in the System	81.05	87.82	81.21	77.75	84.81	82.53
7. Time Spent in the Shop	58.65	59.97	59.49	58.70	60.12	59.39
8. Average Job Tardiness	6.77	10.73	5.95	4.46	8.37	7.26
9. Variance of Job Tardiness, Average	114.85	200.66	86.49	60.61	142.15	120.95
10. Average Lateness	-11.07	-4.22	-11.03	-14.38	-7.39	-9.62
11. Variance of Lateness, Average	1038.68	1075.97	901.88	842.27	1029.05	977.57
12. Machine Balance Measure	5.12	5.047	5.04	5.22	5.19	5.12
13. Shop Balance Measure	.66	.60	.58	.54	.63	.60
14. Queue Workload Balance	8.20	8.22	8.21	7.90	9.06	8.32
15. Period Queue Balance	14.15	25.21	15.67	18.79	12.19	17.20
16. Variance of Waiting Time Per Operation, Average	13.15	190.59	184.51	183.55	204.19	189.20
17. Average Queue Length in Number of Jobs (Shop)	2.28	2.36	2.32	2.27	2.36	2.32
18. Variance of Queue Length in Hours of Work, Average (Machine)	54.57	52.58	54.44	52.08	58.80	54.49
19. Variance of Interarrival Times, Average (Machine)	9.80	9.86	9.91	10.12	10.03	9.94
20. Variance of Interarrival Times (Shop)	9.78	9.83	9.87	10.10	10.01	9.92
21. Variance of Work Arrived Per Period, Average (Machine)	25.06	25.01	25.59	25.19	25.33	25.24
22. Variance of Work Arrived Per Period (Shop)	209.19	193.13	216.72	191.13	212.50	204.53
23. Variance of Output, Average Machine	1.90	1.97	1.99	1.99	1.99	1.97
24. Variance of Output (Shop)	23.28	25.04	25.09	25.32	25.22	24.79

Conditions: Low Utilization, Math Pool, Dynamic Slack (1)

Table 22. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	80.23	81.42	81.32	80.61	82.52	81.22
2. Average Number of Jobs in Shop	32.42	33.10	32.01	32.54	34.93	33.02
3. Average Number of Operations for Jobs in the Shop	75.71	77.22	80.61	81.79	72.43	77.55
4. Average Work (Hours) Done for Jobs in Shop	178.83	182.58	192.73	194.94	168.18	183.45
5. Average Work in Process (Hours)	523.10	532.14	519.29	526.02	588.68	537.85
6. Time Spent in the System	89.10	89.38	77.99	79.95	106.01	88.49
7. Time Spent in the Shop	61.94	62.52	60.75	62.07	65.52	62.56
8. Average Job Tardiness	12.58	10.71	3.97	4.78	22.89	10.99
9. Variance of Job Tardiness, Average	405.21	267.90	67.51	77.69	569.84	277.63
10. Average Lateness	-2.90	-2.68	-14.19	-12.22	13.89	-3.62
11. Variance of Lateness, Average	1442.10	1082.26	885.36	874.13	1428.87	1142.54
12. Machine Balance Measure	5.53	5.21	5.15	5.26	4.83	5.20
13. Shop Balance Measure	.89	.66	.84	.68	.539	.72
14. Queue Workload Balance	9.21	9.24	8.66	9.34	10.44	9.38
15. Period Queue Balance	18.39	38.96	17.60	20.56	14.37	21.98
16. Variance of Waiting Time Per Operation, Average	203.10	208.08	181.77	200.70	223.22	203.37
17. Average Queue Length in Number of Jobs (Shop)	2.44	2.50	2.39	2.45	2.69	2.49
18. Variance of Queue Length in Hours of Work, Average (Machine)	57.68	60.06	56.08	61.88	66.80	60.50
19. Variance of Interarrival Times, Average (Machine)	10.57	10.31	10.14	10.09	9.76	10.17
20. Variance of Interarrival Times (Shop)	10.54	10.28	10.13	10.08	9.75	10.16
21. Variance of Work Arrived Per Period, Average (Machine)	25.76	25.76	27.02	26.11	25.81	26.09
22. Variance of Work Arrived Per Period (Shop)	241.58	216.37	259.29	215.93	202.09	227.05
23. Variance of Output, Average Machine	2.04	1.98	2.02	2.02	1.92	2.00
24. Variance of Output (Shop)	30.08	26.02	29.51	27.30	22.69	27.12

Conditions: Low Utilization, Math Pool, Dynamic Slack Per Operation (2)

Table 23. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.71	81.52	81.26	81.06	81.09	81.33
2. Average Number of Jobs in Shop	29.86	29.45	29.26	29.80	29.40	29.55
3. Average Number of Operations for Jobs in the Shop	95.22	95.06	93.71	96.31	93.69	94.80
4. Average Work (Hours) Done for Jobs in Shop	228.10	226.48	222.42	231.06	222.83	226.18
5. Average Work in Process (Hours)	496.48	487.75	485.40	493.99	486.71	490.07
6. Time Spent in the System	65.17	64.28	63.82	64.39	63.32	64.20
7. Time Spent in the Shop	56.80	56.31	55.41	56.57	55.80	56.18
8. Average Job Tardiness	12.14	12.27	11.63	11.50	11.03	11.71
9. Variance of Job Tardiness, Average	892.83	901.18	862.36	769.36	754.56	836.06
10. Average Lateness	-27.04	-27.79	-28.38	-27.76	-28.83	-27.96
11. Variance of Lateness, Average	3446.71	3529.03	3391.39	3249.30	3218.43	3366.97
12. Machine Balance Measure	5.52	5.22	6.65	5.57	5.55	5.50
13. Shop Balance Measure	1.52	1.06	1.51	1.48	1.60	1.43
14. Queue Workload Balance	6.23	6.90	6.08	6.56	6.12	6.38
15. Period Queue Balance	17.91	65.64	18.75	18.35	11.74	26.48
16. Variance of Waiting Time Per Operation, Average	245.85	262.12	237.51	226.84	224.78	239.42
17. Average Queue Length in Number of Jobs (Shop)	2.17	2.13	2.11	2.17	2.13	2.14
18. Variance of Queue Length in Hours of Work, Average (Machine)	59.29	67.05	59.51	60.74	62.54	61.83
19. Variance of Interarrival Times, Average (Machine)	10.91	9.58	10.27	10.19	10.48	10.29
20. Variance of Interarrival Times (Shop)	10.85	9.57	10.25	10.76	10.45	10.26
21. Variance of Work Arrived Per Period, Average (Machine)	24.86	24.67	24.69	24.79	24.64	24.73
22. Variance of Work Arrived Per Period (Shop)	381.42	331.29	362.41	379.04	394.40	369.71
23. Variance of Output, Average Machine	2.01	1.97	2.07	2.05	2.09	2.04
24. Variance of Output (Shop)	41.29	35.27	41.47	39.11	42.44	39.92

Conditions: Low Utilization, Math Pool, Expected Work in Next Queue (3)

Table 24. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.79	81.67	81.74	81.14	81.46	81.56
2. Average Number of Jobs in Shop	22.73	23.08	23.24	22.70	22.82	22.91
3. Average Number of Operations for Jobs in the Shop	58.45	59.84	59.56	59.16	58.44	59.09
4. Average Work (Hours) Done for Jobs in Shop	134.24	138.05	135.61	135.13	134.19	135.44
5. Average Work in Process (Hours)	412.66	421.03	421.42	412.16	412.83	416.02
6. Time Spent in the System	51.92	53.61	54.78	51.53	51.63	52.69
7. Time Spent in the Shop	42.97	43.85	44.07	43.17	43.06	43.42
8. Average Job Tardiness	6.49	7.40	7.66	6.33	6.27	6.83
9. Variance of Job Tardiness, Average	398.64	494.52	583.42	399.00	338.89	442.29
10. Average Lateness	-40.34	-38.71	-37.39	-40.68	-40.44	-39.51
11. Variance of Lateness, Average	2734.40	2894.62	2965.62	2690.39	2652.96	2787.59
12. Machine Balance Measure	5.19	5.40	5.51	5.62	5.27	5.40
13. Shop Balance Measure	.90	1.16	1.25	1.41	1.02	1.15
14. Queue Workload Balance	2.68	2.80	2.58	2.49	2.73	2.66
15. Period Queue Balance	6.01	16.46	5.33	5.02	3.50	7.26
16. Variance of Waiting Time Per Operation, Average	118.42	129.31	131.95	112.14	113.66	121.10
17. Average Queue Length in Number of Jobs (Shop)	1.46	1.49	1.51	1.46	1.47	1.48
18. Variance of Queue Length in Hours of Work, Average (Machine)	80.58	86.36	75.72	71.90	78.30	72.57
19. Variance of Interarrival Times, Average (Machine)	10.07	10.33	10.64	10.59	10.27	10.38
20. Variance of Interarrival Times (Shop)	10.04	10.31	10.62	10.58	10.25	10.36
21. Variance of Work Arrived Per Period, Average (Machine)	27.12	26.59	26.53	27.07	26.75	26.81
22. Variance of Work Arrived Per Period (Shop)	314.58	342.79	323.92	342.94	339.58	332.76
23. Variance of Output, Average Machine	1.91	1.89	1.92	1.93	1.82	1.89
24. Variance of Output (Shop)	33.98	36.71	36.23	41.22	35.06	36.64

Conditions: Low Utilization, Math Pool, Shortest Processing Time (4)

Table 25. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.31	81.49	81.17	81.24	81.07	81.26
2. Average Number of Jobs in Shop	22.72	22.89	22.77	22.57	22.63	22.72
3. Average Number of Operations for Jobs in the Shop	59.24	59.65	58.18	58.06	59.03	58.83
4. Average Work (Hours) Done for Jobs in Shop	136.09	137.37	133.48	132.42	135.97	135.07
5. Average Work in Process (Hours)	412.82	416.61	412.89	407.37	411.55	412.25
6. Time Spent in the System	52.16	52.39	51.99	51.20	51.62	51.87
7. Time Spent in the Shop	43.14	43.20	43.23	42.84	42.98	43.08
8. Average Job Tardiness	6.79	6.68	6.69	6.03	6.47	6.53
9. Variance of Job Tardiness, Average	429.77	374.28	394.74	335.41	378.59	382.56
10. Average Lateness	-39.93	-39.70	-40.05	-40.91	-40.50	-40.22
11. Variance of Lateness, Average	2774.20	2726.33	2738.24	2621.62	2698.90	2711.86
12. Machine Balance Measure	5.48	5.52	5.52	5.40	5.55	5.49
13. Shop Balance Measure	1.30	1.19	1.20	1.0	1.33	1.20
14. Queue Workload Balance	2.52	2.53	2.66	2.70	2.58	2.60
15. Period Queue Balance	5.93	9.40	4.20	6.84	3.04	5.88
16. Variance of Waiting Time Per Operation, Average	122.31	112.78	121.26	114.15	112.98	116.70
17. Average Queue Length in Number of Jobs (Shop)	1.46	1.47	1.47	1.45	1.45	1.46
18. Variance of Queue Length in Hours of Work, Average (Machine)	73.79	73.96	80.23	79.79	73.43	76.24
19. Variance of Interarrival Times, Average (Machine)	10.79	10.59	10.92	10.54	10.95	10.76
20. Variance of Interarrival Times (Shop)	10.77	10.57	10.89	10.51	10.93	10.73
21. Variance of Work Arrived Per Period, Average (Machine)	27.26	26.74	27.11	27.50	26.73	27.07
22. Variance of Work Arrived Per Period (Shop)	360.43	342.84	324.78	333.70	358.39	344.03
23. Variance of Output, Average Machine	1.96	1.91	1.91	1.89	1.90	1.91
24. Variance of Output (Shop)	40.67	38.29	40.06	34.91	38.93	38.57

Conditions: Low Utilization, Math Pool, Due Date (5)

Table 26. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.22	81.55	81.71	81.15	81.27	81.38
2. Average Number of Jobs in Shop	30.89	30.45	31.36	31.01	31.04	30.95
3. Average Number of Operations for Jobs in the Shop	80.62	79.21	81.64	80.24	80.91	80.52
4. Average Work (Hours) Done for Jobs in Shop	192.29	188.37	194.02	189.88	193.16	191.54
5. Average Work in Process (Hours)	511.42	504.65	518.87	512.47	515.26	512.53
6. Time Spent in the System	73.82	73.13	73.48	75.78	74.24	74.09
7. Time Spent in the Shop	58.62	57.54	59.01	58.86	58.79	58.56
8. Average Job Tardiness	12.63	12.16	12.25	13.48	12.79	12.66
9. Variance of Job Tardiness, Average	445.70	394.79	416.02	450.19	434.68	428.28
10. Average Lateness	-18.37	-19.07	-18.77	-16.31	-17.87	-18.08
11. Variance of Lateness, Average	2556.12	2462.82	2445.39	2539.92	2524.29	2505.71
12. Machine Balance Measure	5.47	5.24	5.12	5.31	5.20	5.27
13. Shop Balance Measure	.91	.97	.61	.87	.82	.84
14. Queue Workload Balance	6.94	6.17	7.76	7.30	8.00	7.23
15. Period Queue Balance	13.66	35.05	14.18	19.83	13.54	19.25
16. Variance of Waiting Time Per Operation, Average	53.92	47.14	68.44	57.38	63.78	58.13
17. Average Queue Length in Number of Jobs (Shop)	2.28	2.23	2.32	2.29	2.29	2.28
18. Variance of Queue Length in Hours of Work, Average (Machine)	51.62	45.25	57.55	52.02	60.11	53.31
19. Variance of Interarrival Times, Average (Machine)	10.41	10.38	9.95	10.25	9.73	10.14
20. Variance of Interarrival Times (Shop)	10.40	10.36	9.93	10.24	9.72	10.13
21. Variance of Work Arrived Per Period, Average (Machine)	26.43	25.23	23.28	25.72	26.50	25.43
22. Variance of Work Arrived Per Period (Shop)	290.94	267.09	235.29	253.45	250.38	259.43
23. Variance of Output, Average Machine	2.01	1.99	1.94	2.01	1.93	1.98
24. Variance of Output (Shop)	31.59	32.88	25.06	27.82	26.20	28.71

Conditions: Low Utilization, Math Pool, First Come First Served (6)

Table 27. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.05	81.47	81.26	81.15	81.16	81.22
2. Average Number of Jobs in Shop	33.54	33.70	32.69	32.40	33.19	33.10
3. Average Number of Operations for Jobs in the Shop	70.81	71.54	70.14	63.39	70.27	70.43
4. Average Work (Hours) Done for Jobs in Shop	168.58	169.56	166.71	164.52	166.72	167.22
5. Average Work in Process (Hours)	552.65	554.91	540.30	535.06	546.25	545.83
6. Time Spent in the System	78.34	78.63	74.76	73.20	77.12	76.41
7. Time Spent in the Shop	63.59	63.63	61.95	61.40	63.02	62.72
8. Average Job Tardiness	4.77	4.91	3.60	2.96	4.46	4.14
9. Variance of Job Tardiness, Average	68.77	71.02	46.77	34.87	66.75	57.64
10. Average Lateness	-13.75	-13.41	-17.46	-18.91	-15.09	-15.72
11. Variance of Lateness, Average	871.78	824.78	882.84	799.06	905.56	856.80
12. Machine Balance Measure	5.27	5.29	5.22	5.27	5.27	5.26
13. Shop Balance Measure	.75	.84	.70	.64	.70	.73
14. Queue Workload Balance	10.27	9.06	9.48	8.98	9.60	9.48
15. Period Queue Balance	22.02	34.35	16.17	23.25	13.24	21.81
16. Variance of Waiting Time Per Operation, Average	237.40	215.43	208.79	211.30	222.25	219.03
17. Average Queue Length in Number of Jobs (Shop)	2.54	2.56	2.46	2.43	2.51	2.50
18. Variance of Queue Length in Hours of Work, Average (Machine)	71.18	65.04	68.02	68.34	67.55	68.03
19. Variance of Interarrival Times, Average (Machine)	10.49	10.11	10.16	10.22	10.46	10.29
20. Variance of Interarrival Times (Shop)	10.47	10.09	10.14	10.21	10.45	10.27
21. Variance of Work Arrived Per Period, Average (Machine)	27.28	27.93	26.58	27.30	26.91	27.20
22. Variance of Work Arrived Per Period (Shop)	291.85	298.95	271.82	275.72	266.89	281.05
23. Variance of Output, Average Machine	1.94	1.99	1.97	1.97	1.98	1.97
24. Variance of Output (Shop)	27.32	27.64	28.06	28.75	27.67	27.89

Conditions: Low Utilization, Pool Heuristics, Dynamic Slack (1)

Table 28. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.33	81.63	81.22	81.12	82.22	81.50
2. Average Number of Jobs in Shop	34.30	34.56	34.39	34.59	35.05	34.58
3. Average Number of Operations for Jobs in the Shop	85.49	87.72	86.95	88.18	84.59	86.59
4. Average Work (Hours) Done for Jobs in Shop	206.78	212.06	210.96	212.68	202.72	209.04
5. Average Work in Process (Hours)	558.48	563.68	562.17	564.10	573.98	564.48
6. Time Spent in the System	78.18	77.22	77.04	76.81	82.06	78.26
7. Time Spent in the Shop	65.00	65.27	65.30	65.67	65.94	65.44
8. Average Job Tardiness	3.76	3.21	2.70	2.81	6.23	3.74
9. Variance of Job Tardiness, Average	64.46	41.97	35.81	37.76	122.66	60.53
10. Average Lateness	-13.91	-14.85	-15.12	-15.38	-10.05	-13.86
11. Variance of Lateness, Average	841.13	791.16	753.13	760.01	972.27	823.54
12. Machine Balance Measure	5.43	5.18	5.37	5.28	4.96	5.24
13. Shop Balance Measure	.97	.79	.93	.81	.75	.85
14. Queue Workload Balance	9.79	9.97	10.22	10.44	10.73	10.23
15. Period Queue Balance	22.18	43.25	24.65	31.54	24.57	29.24
16. Variance of Waiting Time Per Operation, Average	206.17	221.70	220.95	224.98	245.53	223.87
17. Average Queue Length in Number of Jobs (Shop)	2.62	2.64	2.63	2.65	2.68	2.64
18. Variance of Queue Length in Hours of Work, Average (Machine)	65.30	70.93	71.46	75.62	76.71	72.00
19. Variance of Interarrival Times, Average (Machine)	10.48	10.36	10.60	10.26	10.09	10.36
20. Variance of Interarrival Times (Shop)	10.45	10.34	10.58	10.25	10.07	10.34
21. Variance of Work Arrived Per Period, Average (Machine)	26.80	27.34	26.95	27.35	26.66	27.02
22. Variance of Work Arrived Per Period (Shop)	303.83	307.71	311.05	301.43	303.53	305.51
23. Variance of Output, Average Machine	2.01	1.98	1.96	1.94	1.98	1.97
24. Variance of Output (Shop)	31.70	27.35	31.58	29.92	29.03	29.92

Conditions: Low Utilization, Pool Heuristics, Dynamic Slack Per Operation (2)

Table 29. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.66	81.52	81.20	81.11	81.09	81.32
2. Average Number of Jobs in Shop	30.32	29.62	29.75	29.53	29.39	29.72
3. Average Number of Operations for Jobs in the Shop	97.96	95.46	95.20	95.94	94.37	95.79
4. Average Work (Hours) Done for Jobs in Shop	234.12	229.22	226.73	230.41	226.72	229.44
5. Average Work in Process (Hours)	504.13	495.40	494.73	495.72	488.90	495.78
6. Time Spent in the System	66.94	64.58	65.58	64.32	63.93	65.07
7. Time Spent in the Shop	57.75	56.12	56.50	56.09	55.77	56.44
8. Average Job Tardiness	12.91	12.00	12.35	12.16	11.54	12.19
9. Variance of Job Tardiness, Average	1005.34	831.99	984.11	884.80	763.76	894.00
10. Average Lateness	-25.43	-27.59	-26.54	-27.78	-28.23	-27.11
11. Variance of Lateness, Average	3590.22	3365.37	3511.10	3450.12	3286.99	3440.76
12. Machine Balance Measure	5.48	5.17	5.48	5.50	5.64	5.45
13. Shop Balance Measure	1.50	1.04	1.45	1.50	1.58	1.41
14. Queue Workload Balance	6.70	7.11	6.71	6.65	6.43	6.72
15. Period Queue Balance	15.52	54.71	24.39	18.56	10.93	24.82
16. Variance of Waiting Time Per Operation, Average	268.63	259.78	257.35	203.19	229.94	243.78
17. Average Queue Length in Number of Jobs (Shop)	2.22	2.15	2.16	2.14	2.13	2.16
18. Variance of Queue Length in Hours of Work, Average (Machine)	63.50	74.09	64.16	67.14	66.49	67.08
19. Variance of Interarrival Times, Average (Machine)	10.86	9.60	10.42	10.14	10.62	10.33
20. Variance of Interarrival Times (Shop)	10.83	9.58	10.42	10.12	10.59	10.31
21. Variance of Work Arrived Per Period, Average (Machine)	26.51	24.91	24.77	24.88	25.18	25.25
22. Variance of Work Arrived Per Period (Shop)	378.14	337.41	400.06	374.23	395.56	377.08
23. Variance of Output, Average Machine	2.05	1.98	2.03	2.10	1.99	2.03
24. Variance of Output (Shop)	41.08	33.83	42.00	41.07	41.45	39.89

Conditions: Low Utilization, Pool Heuristics, Expected Work in Next Queue (3)

Table 30. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.63	81.58	81.65	81.15	81.49	81.50
2. Average Number of Jobs in Shop	23.04	23.62	23.48	22.93	23.22	23.26
3. Average Number of Operations for Jobs in the Shop	59.94	61.27	60.17	58.82	59.97	60.03
4. Average Work (Hours) Done for Jobs in Shop	138.16	141.43	138.35	134.26	137.13	137.87
5. Average Work in Process (Hours)	421.33	429.59	429.68	417.12	422.09	423.96
6. Time Spent in the System	52.10	54.13	54.63	51.89	52.27	53.00
7. Time Spent in the Shop	43.63	45.15	44.78	43.51	43.86	44.19
8. Average Job Tardiness	6.68	7.81	7.79	6.44	6.98	7.14
9. Variance of Job Tardiness, Average	410.04	592.49	616.65	377.47	485.72	492.47
10. Average Lateness	-40.16	-38.16	-37.67	-40.24	-39.80	-39.15
11. Variance of Lateness, Average	2749.44	3025.23	3022.81	2684.18	2854.74	2867.28
12. Machine Balance Measure	5.25	5.35	5.48	5.55	5.34	5.39
13. Shop Balance Measure	.97	1.18	1.28	1.39	1.09	1.18
14. Queue Workload Balance	2.83	3.05	2.76	2.59	2.92	2.83
15. Period Queue Balance	6.17	15.87	7.03	6.43	3.41	7.78
16. Variance of Waiting Time Per Operation, Average	145.43	173.86	160.06	126.14	145.36	150.17
17. Average Queue Length in Number of Jobs (Shop)	1.49	1.55	1.53	1.48	1.51	1.51
18. Variance of Queue Length in Hours of Work, Average (Machine)	92.36	100.02	88.95	77.46	92.68	90.29
19. Variance of Interarrival Times, Average (Machine)	10.35	10.47	10.64	10.83	10.46	10.55
20. Variance of Interarrival Times (Shop)	10.32	10.44	10.62	10.81	10.43	10.52
21. Variance of Work Arrived Per Period, Average (Machine)	26.99	33.67	26.74	27.70	26.59	28.34
22. Variance of Work Arrived Per Period (Shop)	378.86	376.63	388.06	389.83	371.24	380.92
23. Variance of Output, Average Machine	1.90	1.91	1.86	1.90	1.82	1.88
24. Variance of Output (Shop)	37.91	37.43	39.17	40.98	36.89	38.48

Conditions: Low Utilization, Pool Heuristics, Shortest Processing Time (4)

Table 31. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.29	81.51	81.15	81.29	81.04	81.26
2. Average Number of Jobs in Shop	23.10	23.39	23.33	22.77	23.27	23.17
3. Average Number of Operations for Jobs in the Shop	60.04	60.98	60.07	58.97	60.31	60.07
4. Average Work (Hours) Done for Jobs in Shop	138.21	141.53	139.15	136.33	139.77	139.00
5. Average Work in Process (Hours)	421.60	428.20	427.70	416.11	425.47	423.82
6. Time Spent in the System	52.67	52.62	52.78	51.10	53.04	52.44
7. Time Spent in the Shop	44.05	44.19	44.26	53.15	44.18	43.97
8. Average Job Tardiness	7.07	7.07	6.98	6.24	6.98	6.87
9. Variance of Job Tardiness, Average	480.49	453.44	446.18	427.64	421.27	445.80
10. Average Lateness	-39.59	-39.47	-39.53	-40.91	-39.17	-39.73
11. Variance of Lateness, Average	2852.13	2830.47	2827.95	2731.83	2767.16	2801.91
12. Machine Balance Measure	5.49	5.41	5.53	5.37	5.57	5.47
13. Shop Balance Measure	1.28	1.20	1.21	.99	1.27	1.19
14. Queue Workload Balance	2.74	2.81	2.87	2.86	2.94	2.84
15. Period Queue Balance	5.73	8.99	3.87	7.33	3.06	5.80
16. Variance of Waiting Time Per Operation, Average	145.63	141.90	145.86	139.85	142.11	143.07
17. Average Queue Length in Number of Jobs (Shop)	1.50	1.51	1.52	1.46	1.52	1.50
18. Variance of Queue Length in Hours of Work, Average (Machine)	87.05	88.33	93.62	92.52	92.73	90.85
19. Variance of Interarrival Times, Average (Machine)	11.07	10.36	10.85	10.34	10.78	10.68
20. Variance of Interarrival Times (Shop)	11.04	10.35	10.84	10.31	10.76	10.66
21. Variance of Work Arrived Per Period, Average (Machine)	27.36	26.99	28.23	28.09	28.11	27.76
22. Variance of Work Arrived Per Period (Shop)	373.30	382.95	372.25	357.81	413.17	379.90
23. Variance of Output, Average Machine	1.92	1.86	1.95	1.86	1.90	1.90
24. Variance of Output (Shop)	38.53	37.14	40.03	37.19	39.94	38.57

Conditions: Low Utilization, Pool Heuristics, Due Date (5)

Table 32. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	81.16	81.37	81.66	81.32	81.23	81.35
2. Average Number of Jobs in Shop	33.25	33.83	33.72	33.34	33.45	33.52
3. Average Number of Operations for Jobs in the Shop	87.37	88.67	88.81	87.57	87.83	88.05
4. Average Work (Hours) Done for Jobs in Shop	209.38	213.21	213.24	208.68	211.34	211.17
5. Average Work in Process (Hours)	551.63	559.95	559.60	551.94	555.20	555.66
6. Time Spent in the System	73.92	75.33	74.37	74.74	73.88	74.45
7. Time Spent in the Shop	63.06	64.11	63.49	63.24	63.38	63.46
8. Average Job Tardiness	12.97	13.50	13.37	13.44	13.05	13.27
9. Variance of Job Tardiness, Average	499.20	511.34	507.05	511.93	510.11	507.93
10. Average Lateness	-18.24	-16.80	-17.86	-17.44	-18.31	-17.73
11. Variance of Lateness, Average	2583.44	2584.73	2623.20	2633.76	2621.95	2609.42
12. Machine Balance Measure	5.34	5.31	5.16	5.39	5.27	5.29
13. Shop Balance Measure	.99	.96	.64	.99	.87	.89
14. Queue Workload Balance	9.07	9.04	10.19	8.94	10.20	9.49
15. Period Queue Balance	18.28	60.95	23.59	25.74	14.66	28.64
16. Variance of Waiting Time Per Operation, Average	71.98	71.58	80.91	73.75	81.78	76.00
17. Average Queue Length in Number of Jobs (Shop)	2.51	2.57	2.56	2.52	2.53	2.54
18. Variance of Queue Length in Hours of Work, Average (Machine)	68.17	60.69	77.05	65.82	77.29	69.80
19. Variance of Interarrival Times, Average (Machine)	10.22	10.17	10.10	10.53	10.20	10.24
20. Variance of Interarrival Times (Shop)	10.21	10.14	10.09	10.52	10.17	10.23
21. Variance of Work Arrived Per Period, Average (Machine)	26.92	27.66	27.94	27.06	27.85	27.49
22. Variance of Work Arrived Per Period (Shop)	311.99	309.40	287.90	322.21	323.14	310.93
23. Variance of Output, Average Machine	1.98	1.98	1.94	1.96	1.92	1.96
24. Variance of Output (Shop)	30.64	31.01	25.19	33.64	29.69	30.03

Conditions: Low Utilization, Pool Heuristics, First Come First Served (6)

Table 33. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	90.61	90.72	91.25	91.29	91.43	91.06
2. Average Number of Jobs in Shop	74.01	79.39	74.78	71.89	77.52	75.52
3. Average Number of Operations for Jobs in the Shop	112.15	118.02	112.50	111.21	115.24	113.82
4. Average Work (Hours) Done for Jobs in Shop	274.87	288.47	275.50	271.55	282.04	278.49
5. Average Work in Process (Hours)	1189.76	1270.28	1198.74	1155.66	1243.85	1211.66
6. Time Spent in the System	125.07	134.13	125.81	120.06	129.78	126.97
7. Time Spent in the Shop	125.07	134.13	125.81	120.66	129.78	126.97
8. Average Job Tardiness	37.05	45.65	36.15	30.68	39.80	37.87
9. Variance of Job Tardiness, Average	1062.65	1431.29	750.43	571.36	776.04	918.35
10. Average Lateness	33.31	41.84	33.52	27.77	37.46	34.78
11. Variance of Lateness, Average	1463.70	1948.92	1036.12	857.76	1046.84	1270.67
12. Machine Balance Measure	2.80	2.85	2.72	2.67	2.65	2.74
13. Shop Balance Measure	.31	.40	.29	.27	.28	.31
14. Queue Workload Balance	42.41	51.60	40.06	35.99	41.79	42.37
15. Period Queue Balance	92.37	155.07	78.89	70.51	60.25	91.42
16. Variance of Waiting Time Per Operation, Average	1039.13	1223.97	1014.83	897.63	1064.58	1048.03
17. Average Queue Length in Number of Jobs (Shop)	6.50	7.03	6.57	6.28	6.84	6.64
18. Variance of Queue Length in Hours of Work, Average (Machine)	307.16	360.35	286.21	267.27	302.01	304.60
19. Variance of Interarrival Times, Average (Machine)	7.98	8.07	7.78	7.88	8.05	7.95
20. Variance of Interarrival Times (Shop)	7.97	8.05	7.77	7.87	8.04	7.94
21. Variance of Work Arrived Per Period, Average (Machine)	31.86	30.69	30.13	31.29	31.11	31.02
22. Variance of Work Arrived Per Period (Shop)	304.49	268.19	264.79	251.35	275.45	272.85
23. Variance of Output, Average Machine	2.06	2.12	2.09	2.04	2.15	2.09
24. Variance of Output (Shop)	23.82	26.13	23.01	21.66	24.08	23.74

Conditions: High Utilization, No Pool, Dynamic Slack (1)

Table 34. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	90.64	90.88	90.92	91.08	91.51	91.01
2. Average Number of Jobs in Shop	73.82	78.12	75.20	74.47	78.30	75.98
3. Average Number of Operations for Jobs in the Shop	113.66	113.77	112.82	111.99	112.25	112.90
4. Average Work (Hours) Done for Jobs in Shop	278.01	277.71	275.67	271.75	274.46	275.52
5. Average Work in Process (Hours)	1195.91	1262.67	1214.10	1202.12	1264.64	1227.89
6. Time Spent in the System	124.08	131.21	126.77	123.64	130.66	127.27
7. Time Spent in the Shop	124.08	131.21	126.77	123.64	130.66	127.27
8. Average Job Tardiness	35.47	41.69	36.61	33.72	39.59	37.42
9. Variance of Job Tardiness, Average	1671.51	1617.28	1441.71	1133.84	1192.93	1411.45
10. Average Lateness	32.54	39.09	34.65	31.57	38.12	35.19
11. Variance of Lateness, Average	1997.05	1955.09	1645.58	1376.60	1357.18	1666.30
12. Machine Balance Measure	2.88	2.76	2.71	2.69	2.54	2.72
13. Shop Balance Measure	.38	.35	.33	.30	.29	.33
14. Queue Workload Balance	44.35	48.00	44.66	41.93	42.35	44.26
15. Period Queue Balance	111.48	176.06	98.89	102.26	71.92	112.12
16. Variance of Waiting Time Per Operation, Average	1136.80	1246.55	1158.79	1063.58	1189.32	1159.01
17. Average Queue Length in Number of Jobs (Shop)	6.48	6.91	6.61	6.54	6.92	6.69
18. Variance of Queue Length in Hours of Work, Average (Machine)	326.28	346.18	323.21	310.59	308.58	322.97
19. Variance of Interarrival Times, Average (Machine)	7.83	7.86	7.74	7.91	7.62	7.79
20. Variance of Interarrival Times (Shop)	7.81	7.83	7.73	7.88	7.61	7.77
21. Variance of Work Arrived Per Period, Average (Machine)	29.89	31.83	31.01	29.54	30.34	30.52
22. Variance of Work Arrived Per Period (Shop)	300.22	294.62	271.22	290.84	267.91	284.96
23. Variance of Output, Average Machine	2.06	2.09	2.01	2.04	2.07	2.05
24. Variance of Output (Shop)	24.96	26.27	22.09	22.52	22.66	23.70

Conditions: High Utilization, No Pool, Dynamic Slack Per Operation (2)

Table 35. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	92.26	91.80	91.95	91.61	92.86	92.10
2. Average Number of Jobs in Shop	68.11	64.98	71.94	65.20	77.45	69.34
3. Average Number of Operations for Jobs in the Shop	252.77	242.48	274.99	241.99	293.26	261.10
4. Average Work (Hours) Done for Jobs in Shop	622.98	606.06	685.79	598.93	729.57	648.67
5. Average Work in Process (Hours)	1141.76	1111.32	1215.42	1097.67	1287.08	1170.65
6. Time Spent in the System	114.86	110.84	122.15	108.56	125.68	116.42
7. Time Spent in the Shop	114.86	110.84	122.15	108.56	125.68	116.42
8. Average Job Tardiness	51.00	48.27	56.60	44.91	59.13	51.98
9. Variance of Job Tardiness, Average	13031.89	14960.45	16271.68	9609.75	22326.03	15239.96
10. Average Lateness	22.98	18.55	29.91	16.42	33.20	24.11
11. Variance of Lateness, Average	17313.19	19261.06	20621.24	13540.69	26656.03	19478.44
12. Machine Balance Measure	2.54	2.56	2.68	2.76	2.41	2.59
13. Shop Balance Measure	.56	.43	.67	.60	.63	.58
14. Queue Workload Balance	29.78	27.60	39.90	26.23	33.40	31.38
15. Period Queue Balance	114.27	216.93	104.39	101.71	101.57	127.77
16. Variance of Waiting Time Per Operation, Average	2799.39	3139.09	3689.74	2214.27	4625.89	3293.68
17. Average Queue Length in Number of Jobs (Shop)	5.89	5.58	6.28	5.61	6.72	6.02
18. Variance of Queue Length in Hours of Work, Average (Machine)	459.15	399.81	536.81	355.13	454.41	441.06
19. Variance of Interarrival Times, Average (Machine)	8.12	7.92	8.10	8.00	7.88	8.00
20. Variance of Interarrival Times (Shop)	8.10	7.91	8.09	7.99	7.88	7.99
21. Variance of Work Arrived Per Period, Average (Machine)	29.67	29.39	30.00	28.92	30.26	29.65
22. Variance of Work Arrived Per Period (Shop)	388.67	394.76	373.18	389.66	366.51	382.56
23. Variance of Output, Average Machine	2.16	2.10	2.19	2.22	2.21	2.18
24. Variance of Output (Shop)	31.74	27.16	29.96	32.03	31.77	30.53

Conditions: High Utilization, No Pool, Expected Work in Next Queue (3)

Table 36. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	91.18	91.65	92.70	91.86	91.96	91.87
2. Average Number of Jobs in Shop	43.64	44.54	49.00	45.57	45.30	45.61
3. Average Number of Operations for Jobs in the Shop	110.74	113.45	124.33	115.89	114.91	115.86
4. Average Work (Hours) Done for Jobs in Shop	268.08	272.78	307.20	279.76	278.32	281.23
5. Average Work in Process (Hours)	858.51	873.79	979.50	893.35	893.21	899.67
6. Time Spent in the System	73.01	76.35	82.22	73.48	75.23	76.06
7. Time Spent in the Shop	73.01	76.35	82.22	73.48	75.23	76.06
8. Average Job Tardiness	24.96	27.53	32.70	24.89	26.39	27.29
9. Variance of Job Tardiness, Average	7259.98	7605.05	.24	6512.14	7426.46	7903.37
10. Average Lateness	-18.93	-16.03	-9.70	-18.87	-17.16	-16.14
11. Variance of Lateness, Average	11246.22	11817.95	15264.08	10508.94	11503.32	12068.10
12. Machine Balance Measure	2.89	2.68	2.36	2.65	2.67	2.65
13. Shop Balance Measure	.55	.47	.43	.53	.44	.48
14. Queue Workload Balance	9.03	9.08	11.29	9.59	8.81	9.56
15. Period Queue Balance	27.67	61.97	33.99	28.82	13.70	33.23
16. Variance of Waiting Time Per Operation, Average	1576.92	1657.52	2435.37	1503.74	1640.60	1762.83
17. Average Queue Length in Number of Jobs (Shop)	3.45	3.54	3.98	3.64	3.61	3.64
18. Variance of Queue Length in Hours of Work, Average (Machine)	486.20	486.36	663.72	523.62	470.71	526.12
19. Variance of Interarrival Times, Average (Machine)	8.34	8.40	8.13	8.10	8.37	8.27
20. Variance of Interarrival Times (Shop)	8.32	8.39	8.11	8.07	8.35	8.25
21. Variance of Work Arrived Per Period, Average (Machine)	31.36	31.51	32.52	31.53	32.07	31.80
22. Variance of Work Arrived Per Period (Shop)	464.92	460.10	452.24	447.90	485.63	462.16
23. Variance of Output, Average Machine	1.98	1.90	1.88	1.93	2.01	1.94
24. Variance of Output (Shop)	38.31	38.63	36.86	36.17	41.34	38.26

Conditions: High Utilization, No Pool, Shortest Processing Time (4)

Table 37. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	90.92	90.98	91.35	91.28	92.05	91.32
2. Average Number of Jobs in Shop	81.81	84.92	83.27	75.90	92.08	83.60
3. Average Number of Operations for Jobs in the Shop	210.46	219.22	215.16	196.71	236.66	215.64
4. Average Work (Hours) Done for Jobs in Shop	527.97	552.16	539.19	493.45	596.39	541.83
5. Average Work in Process (Hours)	1347.66	1397.05	1365.45	1251.51	1511.91	1374.72
6. Time Spent in the System	137.55	143.32	140.44	127.57	152.69	140.31
7. Time Spent in the Shop	137.55	143.32	140.44	127.57	152.69	140.31
8. Average Job Tardiness	58.75	62.34	59.98	48.39	69.63	59.82
9. Variance of Job Tardiness, Average	4565.75	4359.00	4098.99	2881.15	4810.05	4142.99
10. Average Lateness	45.62	51.14	48.51	35.58	60.40	48.25
11. Variance of Lateness, Average	6757.20	6331.31	5996.70	4730.56	6547.85	6072.72
12. Machine Balance Measure	2.83	2.72	2.66	2.58	2.50	2.66
13. Shop Balance Measure	.42	.38	.37	.30	.28	.35
14. Queue Workload Balance	53.39	54.67	54.02	39.73	56.07	51.58
15. Period Queue Balance	139.88	181.85	163.50	105.51	109.74	140.10
16. Variance of Waiting Time Per Operation, Average	374.77	381.10	381.76	281.32	393.47	362.48
17. Average Queue Length in Number of Jobs (Shop)	7.27	7.59	7.42	6.68	8.29	7.45
18. Variance of Queue Length in Hours of Work, Average (Machine)	384.28	390.47	384.76	291.01	398.05	369.71
19. Variance of Interarrival Times, Average (Machine)	7.92	7.83	8.09	7.89	7.75	7.90
20. Variance of Interarrival Times (Shop)	7.91	7.81	8.08	7.87	7.73	7.88
21. Variance of Work Arrived Per Period, Average (Machine)	30.97	31.63	29.55	30.53	31.31	30.80
22. Variance of Work Arrived Per Period (Shop)	309.93	322.93	307.48	288.79	311.88	308.20
23. Variance of Output, Average Machine	2.10	2.08	2.05	2.05	2.09	2.07
24. Variance of Output (Shop)	25.98	24.13	23.35	21.75	24.22	23.89

Conditions: High Utilization, No Pool, First Come First Served (6)

Table 38. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	89.67	89.53	89.88	89.60	90.01	89.74
2. Average Number of Jobs in Shop	62.75	64.14	63.24	62.16	62.50	62.96
3. Average Number of Operations for Jobs in the Shop	100.28	99.51	99.73	100.48	98.32	99.66
4. Average Work (Hours) Done for Jobs in Shop	241.06	239.73	241.14	241.42	235.72	239.81
5. Average Work in Process (Hours)	989.24	1013.30	996.97	982.36	985.65	993.50
6. Time Spent in the System	164.14	162.68	168.33	167.25	169.68	166.42
7. Time Spent in the Shop	107.14	109.39	107.02	105.26	105.95	106.95
8. Average Job Tardiness	73.63	73.64	76.53	75.50	78.67	75.59
9. Variance of Job Tardiness, Average	2034.87	2550.06	1770.40	1467.08	1186.70	1801.82
10. Average Lateness	72.25	70.74	76.06	75.14	77.69	74.38
11. Variance of Lateness, Average	2289.75	3123.11	1862.09	1538.83	1383.72	2039.50
12. Machine Balance Measure	3.12	3.21	3.16	3.21	3.07	3.15
13. Shop Balance Measure	.31	.38	.30	.29	.31	.32
14. Queue Workload Balance	29.62	30.18	31.91	29.08	27.33	29.62
15. Period Queue Balance	50.87	84.18	53.31	56.21	37.75	56.46
16. Variance of Waiting Time Per Operation, Average	633.52	660.33	652.11	595.75	573.13	622.97
17. Average Queue Length in Number of Jobs (Shop)	5.38	5.52	5.43	5.32	5.35	5.40
18. Variance of Queue Length in Hours of Work, Average (Machine)	203.54	198.78	223.52	214.39	200.30	208.11
19. Variance of Interarrival Times, Average (Machine)	8.31	8.22	8.21	8.25	8.39	8.28
20. Variance of Interarrival Times (Shop)	8.29	8.21	8.19	8.24	8.37	8.26
21. Variance of Work Arrived Per Period, Average (Machine)	30.11	29.39	29.78	20.66	29.88	29.96
22. Variance of Work Arrived Per Period (Shop)	249.63	231.44	244.16	252.72	241.97	243.98
23. Variance of Output, Average Machine	2.06	2.12	2.02	2.04	2.10	2.07
24. Variance of Output (Shop)	24.03	25.70	20.74	26.13	24.15	24.15

Conditions: High Utilization, Math Pool, Dynamic Slack (1)

Table 39. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	89.34	89.65	89.36	89.58	90.01	89.59
2. Average Number of Jobs in Shop	65.15	62.45	64.37	65.09	63.42	64.10
3. Average Number of Operations for Jobs in the Shop	88.66	88.99	85.31	85.17	85.62	86.75
4. Average Work (Hours) Done for Jobs in Shop	210.58	210.21	201.43	200.62	203.13	205.19
5. Average Work in Process (Hours)						
6. Time Spent in the System	1050.41	1008.66	1039.00	1059.49	1027.09	1036.93
7. Time Spent in the Shop	167.16	160.81	171.51	177.86	173.20	170.11
8. Average Job Tardiness	110.60	106.25	108.98	109.48	107.22	108.51
9. Variance of Job Tardiness, Average	76.37	70.39	79.58	85.93	81.55	78.76
10. Average Lateness	3643.14	3021.22	3178.79	2520.05	2057.54	2884.15
11. Variance of Lateness, Average	75.45	68.74	79.26	85.78	80.93	78.03
12. Machine Balance Measure	3827.09	3343.49	3243.91	2552.39	2186.95	3030.77
13. Shop Balance Measure	3.26	3.13	3.28	3.30	3.06	3.21
14. Queue Workload Balance	.41	.36	.30	.32	.31	.34
15. Period Queue Balance	35.46	28.14	34.06	35.00	28.32	32.20
16. Variance of Waiting Time Per Operation, Average	54.24	103.14	55.96	59.80	43.80	63.39
17. Average Queue Length in Number of Jobs (Shop)	933.90	735.39	904.26	894.17	733.26	840.20
18. Variance of Queue Length in Hours of Work, Average (Machine)	5.62	5.35	5.54	5.62	5.44	5.51
19. Variance of Interarrival Times, Average (Machine)	242.27	191.51	232.49	256.09	199.74	224.42
20. Variance of Interarrival Times (Shop)	8.03	8.23	8.37	8.39	8.16	8.24
21. Variance of Work Arrived Per Period, Average (Machine)	8.02	8.22	8.36	8.38	8.14	8.22
22. Variance of Work Arrived Per Period (Shop)	29.56	29.90	29.67	29.49	30.34	29.85
23. Variance of Output, Average Machine	241.52	215.06	225.18	239.98	265.80	237.51
24. Variance of Output (Shop)	2.07	2.02	2.05	2.08	2.08	2.06

Conditions: High Utilization, Math Pool, Dynamic Slack Per Operation (2)

Table 40. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	92.23	91.87	91.88	91.46	92.78	92.04
2. Average Number of Jobs in Shop	57.22	54.17	59.29	54.57	61.16	57.28
3. Average Number of Operations for Jobs in the Shop	207.57	194.20	220.86	198.32	227.62	209.71
4. Average Work (Hours) Done for Jobs in Shop	510.62	483.48	556.20	494.33	564.90	521.91
5. Average Work in Process (Hours)	959.30	922.17	1009.34	924.46	1028.23	968.70
6. Time Spent in the System	108.07	103.52	113.58	101.63	115.23	108.41
7. Time Spent in the Shop	95.04	91.23	99.13	90.44	100.71	95.31
8. Average Job Tardiness	41.13	38.29	46.41	36.29	46.98	41.82
9. Variance of Job Tardiness, Average	8970.58	9033.83	11011.65	6645.90	13841.58	9900.71
10. Average Lateness	15.91	11.18	21.41	9.62	22.91	16.21
11. Variance of Lateness, Average	12289.52	12430.65	14576.93	9857.24	17318.64	13294.60
12. Machine Balance Measure	2.65	2.58	2.72	2.87	2.51	2.67
13. Shop Balance Measure	.56	.40	.67	.60	.60	.57
14. Queue Workload Balance	17.41	15.55	22.56	15.75	18.29	17.91
15. Period Queue Balance	46.04	105.57	72.78	57.08	48.05	65.90
16. Variance of Waiting Time Per Operation, Average	1808.31	1776.68	2131.98	1393.11	2674.74	1956.96
17. Average Queue Length in Number of Jobs (Shop)	4.80	4.50	5.01	4.54	5.19	4.81
18. Variance of Queue Length in Hours of Work, Average (Machine)	272.38	242.43	339.98	234.92	265.11	270.96
19. Variance of Interarrival Times, Average (Machine)	7.86	7.73	7.89	7.93	7.78	7.84
20. Variance of Interarrival Times (Shop)	7.85	7.72	7.88	7.92	7.77	7.83
21. Variance of Work Arrived Per Period, Average (Machine)	27.27	27.91	27.05	28.38	27.06	27.53
22. Variance of Work Arrived Per Period (Shop)	338.86	286.20	314.48	334.77	291.26	313.11
23. Variance of Output, Average Machine	2.12	2.06	2.12	2.12	2.10	2.10
24. Variance of Output (Shop)	33.09	27.21	31.96	32.55	29.04	30.77

Conditions: High Utilization, Math Pool, Expected Work in Next Queue (3)

Table 41. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	91.16	91.77	92.49	91.64	91.91	91.79
2. Average Number of Jobs in Shop	36.27	37.60	39.56	37.18	37.16	37.55
3. Average Number of Operations for Jobs in the Shop	93.54	98.51	100.67	96.23	95.73	96.94
4. Average Work (Hours) Done for Jobs in Shop	223.56	237.03	243.42	229.74	228.45	232.44
5. Average Work in Process (Hours)	691.14	716.27	763.44	708.12	705.52	716.90
6. Time Spent in the System	77.31	80.78	90.31	79.37	78.02	81.16
7. Time Spent in the Shop	60.86	63.12	65.02	61.53	61.90	62.49
8. Average Job Tardiness	21.27	22.87	27.79	21.83	21.28	23.01
9. Variance of Job Tardiness, Average	4051.70	4610.63	5782.69	3640.60	3784.67	4374.06
10. Average Lateness	-14.44	-11.72	-1.91	-12.60	-14.20	-10.97
11. Variance of Lateness, Average	7140.91	7716.56	8869.45	6669.22	6849.85	7449.20
12. Machine Balance Measure	2.88	2.69	2.43	2.79	2.61	2.68
13. Shop Balance Measure	.46	.38	.38	.52	.42	.43
14. Queue Workload Balance	5.07	5.34	6.36	5.02	4.98	5.35
15. Period Queue Balance	11.56	30.76	13.30	10.45	7.13	14.64
16. Variance of Waiting Time Per Operation, Average	727.31	813.98	1027.89	665.01	705.71	787.98
17. Average Queue Length in Number of Jobs (Shop)	2.72	2.84	3.03	2.80	2.80	2.84
18. Variance of Queue Length in Hours of Work, Average (Machine)	229.20	254.07	329.67	233.46	228.64	255.01
19. Variance of Interarrival Times, Average (Machine)	8.17	7.91	7.81	8.09	7.90	7.98
20. Variance of Interarrival Times (Shop)	8.15	7.89	7.79	8.08	7.89	7.96
21. Variance of Work Arrived Per Period, Average (Machine)	30.39	30.30	28.73	28.70	29.10	29.44
22. Variance of Work Arrived Per Period (Shop)	310.92	293.28	248.49	280.23	295.13	285.61
23. Variance of Output, Average Machine	1.80	1.90	1.86	1.89	1.88	1.87
24. Variance of Output (Shop)	28.24	25.64	24.35	26.54	27.26	26.41

Conditions: High Utilization, Math Pool, Shortest Processing Time (4)

Table 4.2. Simulation Results

	1	2	3	4	5	Avg.
1. Average Shop Utilization	90.31	90.19	90.61	90.29	91.34	90.55
2. Average Number of Jobs in Shop	60.63	66.09	60.30	55.36	67.71	62.02
3. Average Number of Operations for Jobs in the Shop	156.19	170.38	155.35	143.43	174.97	160.06
4. Average Work (Hours) Done for Jobs in Shop	385.01	422.95	382.64	352.48	433.85	395.39
5. Average Work in Process (Hours)	991.82	1081.64	982.67	907.23	1108.46	1014.36
6. Time Spent in the System	142.28	158.93	143.41	129.90	168.27	148.56
7. Time Spent in the Shop	102.97	111.98	101.74	94.10	113.54	104.87
8. Average Job Tardiness	61.37	75.78	60.36	48.34	80.65	65.30
9. Variance of Job Tardiness, Average	3268.33	3731.53	2834.75	2025.94	3128.75	2997.86
10. Average Lateness	50.78	67.26	51.47	38.10	76.22	56.77
11. Variance of Lateness, Average	5124.08	5514.65	4376.32	3538.17	4103.35	4531.31
12. Machine Balance Measure	2.95	2.98	2.87	2.91	2.68	2.88
13. Shop Balance Measure	.36	.36	.34	.26	.29	.32
14. Queue Workload Balance	26.69	31.88	25.45	20.48	31.64	27.23
15. Period Queue Balance	47.84	85.71	54.04	40.38	49.55	55.50
16. Variance of Waiting Time Per Operation, Average	188.94	225.37	178.97	149.64	226.65	193.91
17. Average Queue Length in Number of Jobs (Shop)	5.16	5.71	5.13	4.63	5.86	5.30
18. Variance of Queue Length in Hours of Work, Average (Machine)	192.21	228.23	182.22	150.52	236.16	197.87
19. Variance of Interarrival Times, Average (Machine)	8.11	7.99	8.00	8.06	7.83	8.00
20. Variance of Interarrival Times (Shop)	8.11	7.97	7.99	8.04	7.82	7.99
21. Variance of Work Arrived Per Period, Average (Machine)	28.87	29.79	28.96	28.62	30.30	29.31
22. Variance of Work Arrived Per Period (Shop)	286.28	252.38	264.47	218.82	240.13	252.42
23. Variance of Output, Average Machine	2.06	1.96	2.03	2.01	2.12	2.04
24. Variance of Output (Shop)	24.75	23.51	23.07	20.18	23.49	23.00

Conditions: High Utilization, Math Pool, First Come First Served (6)

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